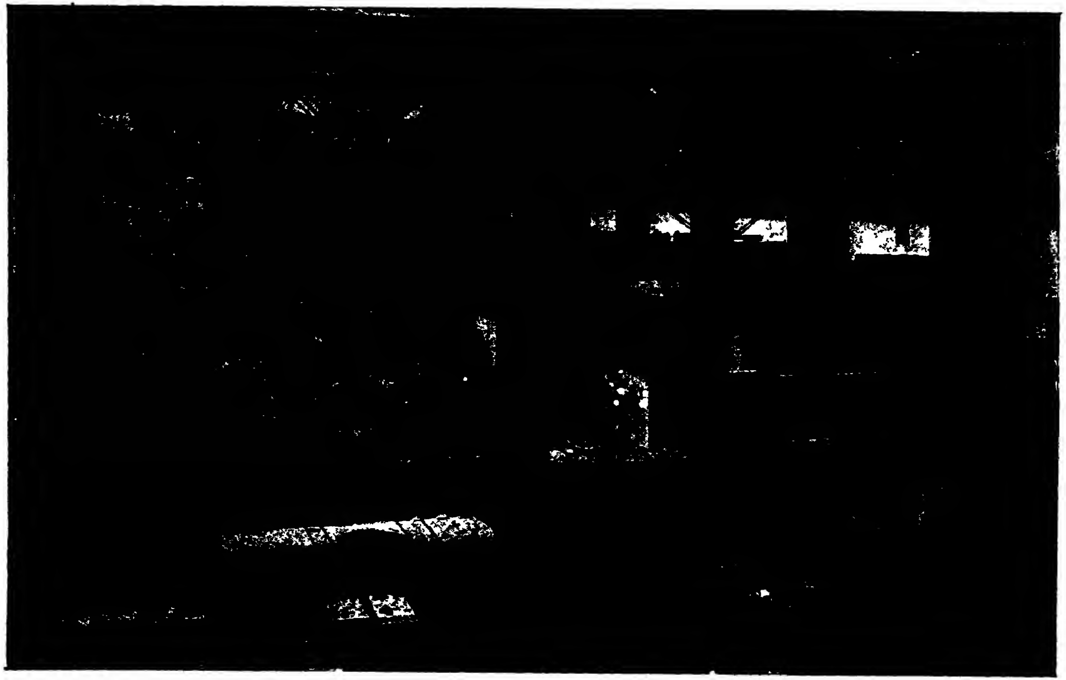

AN ELECTRIC LOCOMOTIVE ERECTING SHOP

Single-phase passenger locomotives for Swiss Federal Railways during erection at Oerlikon Works)

Frontispiece

ELECTRIC TRACTION

A TREATISE ON THE APPLICATION OF ELECTRIC POWER TO TRAMWAYS AND RAILWAYS

BY

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WITH 510 ILLUSTRATIONS AND 8 FOLDING PLATES

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PREFACE

Electric traction on railways has made considerable progress since the first edition of this book was prepared, and, in consequence, a large portion of the book has had to be re-written. Considerable progress has also been made in electric traction on railless routes, and therefore due prominence is given to the trolley omnibus and its equipment.

The general plan and arrangement of the first edition has been retained, but additional worked examples have been included.

In the task of revision the author has had the generous co-operation of a large number of engineers and manufacturers, to whom he is under considerable obligation. Among the former are: Lt.-Col. F. A. Cortez-Leigh (L.M.S. Railway), Mr. G. Hally (Metropolitan Railway), Mr. Herbert Jones (Southern Railway), Mr. W. W. Howell (London Underground Railways). To all these gentlemen the author tenders his heartiest thanks.

The author's thanks are also due to H.M. Ministry of Transport, Messrs. Merz and McLellan, and Mr. F. Lydall.

The manufacturers to whom the author is indebted for the supply of data, drawings, photographs, and blocks, and whom he desires to thank specially are: A.S.E.A. Electric Co. (and the parent company, viz. Allmänna Svenska Elektriska A.B., Vesteras); Messrs. British Brown Boveri; Brown, Boveri & Co. (Baden); British Insulated Cables; The British Thomson-Houston Co.; The English Electric Co.; The General Electric Co. (London); The General Electric Co. (Schenectady); Evershed & Vignoles; Richard Garrett & Sons (Leiston); Hadfields Ltd.; The Metropolitan-Vickers Electrical Co.; Oerlikon Ltd., London (and Mr. G. Wütrich, M.I.E.E., their chief engineer); Maschinenfabrik Oerlikon; Ransomes, Sims & Jefferies; Siemens-Schuckert (Great Britain); Siemens-Schuckertwerke (Berlin); The Westinghouse Electric and Mfg. Co. (East Pittsburg); The Rheostatic Co.

Acknowledgments are due to the technical press from which data and particulars of electrifications have been obtained. The chief publications concerned are: *Electrician*, *Electrical Review*, *Engineering*, *Engineer*, *Electric Railway Journal*, *Electric Journal*, *General Electric Review*, *Railway Gazette*, *Railway Engineer*, *Tramway and Railway World*, *Journal of the Institution of Electrical Engineers*, *Transactions of the American Institute of Electrical Engineers*, *Proceedings of the Institution of Civil Engineers*, *Specifications of the British Engineering Standards Association*.

To the Senate of the University of London, the Examinations Board of the City and Guilds of London Institute, and the Council of the

Institution of Electrical Engineers, the thanks of the author are due for permission to use questions from their examination papers, and, in the case of the Institution of Electrical Engineers, the loan of blocks from the *Journal of the I.E.E.*

The author wishes to express his appreciation of the assistance given to him by his colleagues S. Marsh, D.Sc., Ph.D., and H. C. Mann, B.Sc. (Eng.) Lond., M.I.E.E.

A. T. D.

PREFACE
TO THE FIRST EDITION

This book is intended for engineers and advanced students: it treats of the principles relating to the application of electric power to tramways and railways. Representative examples of modern tramway and railway practice are included, but detailed accounts of electrifications have been omitted, as the latter are treated fully in the technical press.

Generating stations and transmission lines have not been considered, as these could not have been adequately dealt with in the present volume. Moreover, the generation of electrical energy is now a specialized subject and involves considerations which have little bearing on the utilization of the energy for traction purposes.

The subject-matter has been arranged as follows: Mechanics of train movement; motors; control; auxiliary apparatus; rolling stock; detailed study of train movement; track and overhead construction; distributing systems and substations. A number of worked examples have been included in the text, and a collection of 67 examples, taken principally from public examination papers and covering the whole scope of the subject, is given at the end of the volume.

The diagrams in the chapters on "control" have been made as clear as possible; the tracing of control circuits, however, requires practice, and this is best acquired by the study of simplified diagrams such as are given at appropriate places in the text.

The author is under considerable obligation to many engineers and manufacturers who have generously supplied him with data, drawings, photographs, etc. Among the former are: Mr. (now Sir) John A. F. Aspinall, General Manager, Lancashire and Yorkshire Railway; Mr. W. A. Agnew, Chief Mechanical Engineer, London Underground Railways; Mr. (now Sir) Philip Dawson, Consulting Engineer to the London, Brighton and South Coast Railway; Mr. A. L. C. Fell, Chief Officer, London County Council Tramways; Mr. Herbert Jones, Chief Electrical Engineer, London and South-Western Railway: Mr. William S. Murray, Consulting Engineer to the New York, New Haven and Hartford Railroad; Mr. C. W. Mallins, General Manager, Liverpool Corporation Tramways; Mr. A. P. Trotter, Electrical Adviser to the Board of Trade. To all these gentlemen the author tenders his heartiest thanks.

The firms to whom the author is indebted are numerous. Acknowledgments are made throughout the text, and the author desires especially to thank: Messrs. Hadfields, Ltd.; The British Thomson-Houston Co.;

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The British Westinghouse Co.;* Messrs. Dick, Kerr & Co.;† Siemens Bros. Dynamo Works;† Messrs. Brown, Boveri & Co. (and Mr. A. C. Eborall); The Brush Electrical Engineering Co; The J. G. Brill Co.; The British Insulated Cables, Ltd.; Messrs. Brecknell, Munro & Rogers; Messrs. Doulton & Co.; Messrs. Elliott Bros.; The Leeds Forge Co.; The Maschinenfabrik Oerlikon, Oerlikon, Zurich (and Mr. G. Wüthrich); The Società Italiana Westinghouse, Vado Ligure; The Westinghouse Department of Publicity, East Pittsburg, Pa.; The Publication Bureau of the General Electric Co., Schenectady, N Y.

In many cases data and particulars of electrifications have been drawn from the technical press, acknowledgments of which have generally been made in the text. The chief sources of such information have been: *The Tramway and Railway World*, *The Electrician*, *The Electrical Review*, *The Engineer*, *Engineering*, *The Electric Railway Journal*, *The Electric Journal*, *The General Electric Review*, *L'Éclairage Électrique*, the publications of the Engineering Standards Committee, and the *Proceedings* (and *Transactions*) of the following Institutions: The Institution of Electrical Engineers, The American Institute of Electrical Engineers, The Institution of Civil Engineers, The Institution of Mechanical Engineers. To these the author desires to express his indebtedness.

To Mr. A. M. Willcox (Editor of the *Tramway and Railway World*) the author is especially indebted for the use of a number of large half-tone blocks illustrating overhead construction, locomotives, and substations.

To the Senate of the University of London, the Examinations' Board of the City and Guilds of London Institute, and the Council of the Institution of Electrical Engineers, the thanks of the author are due for permission to use questions from their examination papers.

The author wishes to take this opportunity of expressing his appreciation of the valuable assistance—in the form of suggestions, criticisms, MS. and proof reading—given him, during the preparation of the work, by his colleagues Dr. A. W. Ashton, M.I.E.E.; Messrs. J. Beaumont Shaw, A.R.C.S.; and William Thomson, M.A.

A. T. D.

LONDON, 1917.

* Now the Metropolitan-Vickers Electrical Co.
† Now the English Electric Co.

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LIST OF ABBREVIATIONS

Amperes	A.
Centimetre	cm.
Electromotive force	E.M.F.
Foot, feet	ft.
Horse-power	h.p.
Inch	in.
Kilogramme	kg.
Kilometre	kM.
Kilowatt	kW.
Kilowatt-hour	kWh
Mile	ml.
Miles per hour	ml.p.h.
Miles per hour per second	ml.p.h.p.s
Millimetre	mm.
Pound	lb.
Revolutions per minute	r.p.m
Second	sec.
Watt hour	Wh.
Kilo volt	kV.
Volt	V.
Watt	W.
Kilo-volt ampere	kVA.
Revolutions per second	r.p.s.
Root-mean-square	r.m.s.

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CHIEF SYMBOLS

A, a = Cross-sectional area.
a = Number of circuits in armature winding.
B = Flux density (B_m = maximum flux density).
D = Distance (in miles) between stops.
= Distance between conductors of circuit.
D' = Distance (in miles) from start to cut-off.
D_a, D_c, D_w = Diameter of armature, commutator, or driving wheel
E = E.M.F. generated in armature or stator winding.
E_a = Phase E.M.F. of rectifier.
E_d = Output voltage of rectifier.
E_c = Commutator voltage of rotary converter.
E_{av} = Average voltage between commutator segments.
E_s = Static (induced) E.M.F.
= Slip-ring voltage of rotary converter.
E_t = Transformer E.M.F. induced in armature coils short-circuited by brushes.
F = Force or tractive effort.
f = Frequency (cycles per second).
G = Gradient in per cent.
h = Number of hours per annum.
I = Current (I_1, I_2, upper and lower limits, respectively).
I_d = Current output from cathode of rectifier.
J = Energy in watt seconds or joules.
K, k = Constants.
k = Radius of gyration.
= Air-resistance coefficient for shape of end of train
L, l = Length.
L = Inductance.
m = Number of armature coils short-circuited by a brush.
= Number of slip rings in rotary converter.
N = Number of turns per circuit in armature or stator winding.
n = Revolutions.
= Number of anodes in rectifier.
n_s = Synchronous speed in revolutions per minute.
n_c = Cascade synchronous speed.
P = Power.
= Pull on poles in span-wire construction.
p = Number of poles.
= Price (in pence) of 1 kilowatt hour.
Q = Specific electric loading (ampere turns per inch of periphery of armature).
R = Resistance in ohms.
= Total train resistance in lb.
r = Specific train resistance in lb. per ton.

R, r = Radius.

S = Longitudinal exposed surface of coach.

s = "Slip" of rotor of induction motor.

= Half length of span of span-wire.

T, t = Time in seconds.

T = Tension in trolley wire (or catenary wire) at lowest point.

U = Hypothetical speed of train.

V = Speed of train or car in ml.p.h. (V_m = maximum speed, V_a = average speed).

= Terminal voltage.

v_c = Peripheral speed of commutator.

W = Dead weight of train in tons.

= Weight per span of trolley wire (or span wire).

W_e = Effective (or accelerating) weight of train in tons.

w = Weight per foot of trolley wire (or span wire).

X = Reactance.

y = Deflection at dropper in catenary suspension.

z = Distance between trolley-wire and catenary wire at mid-span.

Z = Impedance.

a = Acceleration in ml.p.h.p.s.

β = Braking retardation in ml.p.h.p.s.

β_c = Coasting retardation in ml.p.h.p.s.

β_r = Retardation when braking regeneratively.

Δ = "Delta" connection of three-phase circuits.

δ = Sag of trolley wire (or catenary wire).

η = Efficiency.

Φ = Flux per pole in megalines (Φ_m = maximum flux).

φ = Phase angle between current and E.M.F.

γ = Gear ratio.

= Grading coefficient in rheostat calculations ($= I_2/I_1$).

λ = Ratio exposed transverse surface of coach/cross section of coach body.

= Spacing of droppers in catenary suspension.

= Grading coefficient in rheostat calculations ($=(\Phi_1/I_1)/(\Phi_2/I_2)$).

τ_c = Pitch of commutator segments.

μ = Permeability.

θ = Temperature.

ω = $2\pi \times$ frequency.

$\mathfrak{T}$ = Torque.

NOTES

LOGARITHMS, where used, are to the base 10.

VECTOR DIAGRAMS.—All diagrams have been drawn for *counter-clockwise* rotation.

E.M.F. vectors are represented by an ordinary arrow-head.

Flux vectors are represented by a double arrow-head.

Ampere-turn vectors are represented by a solid arrow-head.

Current vectors are represented by a closed arrow-head.

WEIGHTS.—The British ton (2240 lb.) is used throughout this treatise. All weights relating to Continental and American machines and apparatus have been reduced to this unit.

ELECTRIC TRACTION

CHAPTER I

INTRODUCTION

THE considerations involved in the application of electric power to the working of tramways and railways may be divided into two classes—(1) technical, (2) financial. In the present volume we shall confine our attention to the former.

The **technical considerations** involve the supply of electric power from a generating station to a number of cars or trains which have to operate, over a given track, to a given schedule.

Systems of operation. With tramways the operating system and the voltage are prescribed by the Regulations of the Ministry of Transport (Appendix I), but with railways a choice of systems and voltages (subject to the approval of the Ministry) is possible. Thus tramcars must be supplied with direct current at a voltage not exceeding 600 volts. On the other hand, railway trains may be supplied with either direct or alternating current, at low or high voltage.

Methods of supplying power to cars operating on tramways. Two methods are in use at the present day, viz. (1) the overhead system, (2) the conduit system.

(1) The **overhead system.** An overhead conductor, fed from the generating station at suitable points, is suspended above the track, and current is conveyed from this conductor to the car equipment by means of a suitable current collector—in the form of a trolley wheel or a sliding bow—carried on the car. The track rails are utilized as the return conductor and are connected to the generating station at suitable points.

In some very special cases, however, the return conductor is placed overhead,* and two current collectors are required.

(2) The **conduit system.** Two conductors of opposite polarity, fed from the generating station at suitable points, are supported in a slotted conduit—located either in the centre or at the side of the track—and the current is conveyed from these conductors to the car equipment by means of a current collector, which is carried on the car and passes through the slot in the conduit. Generally, both conductors are supported from insulators, and the track rails do not form part of the conducting system. The conductors in the conduit consist of T-rails arranged thus, ⊣ ⊢.

* The only example, in this country, of an insulated return for overhead tramways occurs on a section of the London County Council tramways in the neighbourhood of Greenwich Observatory.

Comparison of tramway systems. Owing to the cost per mile of trackwork of the **conduit** system being approximately double that of the overhead system,* the former system can only be adopted in those large cities in which the overhead system is undesirable. The only example in this country is the conduit lines of the London County Council tramways, which comprise 122 miles of route (of which 117·5 miles are double track) in and around Central London.†

The **overhead** system—with a single trolley wire and rail return—has been adopted on an extensive scale in this country and abroad, and in Great Britain there are approximately 2500 miles of tramways operating on this system.

The overhead system—with two trolley wires and without track rails—has been adapted to the supply of power to electric omnibuses (called "trolley buses"). This system of **railless,** or trackless trolley, **traction** possesses advantages over a tramway system in that the large expense of the installation and maintenance of the track is avoided.‡ Consequently the system can be utilized as an extension of an existing tramway system to outlying villages which require only an infrequent service of cars. The railless system is also suitable for towns having narrow streets, and in these cases it has obvious advantages over tramways, since railless cars can thread through the traffic. On the other hand, railless cars are necessarily smaller and lighter than the majority of tramcars, while the amount of power required by a railless car is greater than that which would be required by a tramcar of equal weight, on account of the increased resistance to motion.

The overhead equipment for railless cars must, obviously, comprise two conductors of opposite polarity, and the current collector must allow the cars to be piloted through the traffic.

Comparing such a trackless-trolley system with the alternative system of self-propelled electric omnibuses equipped with batteries, the former possesses the advantages of considerably lower maintenance and running costs. Moreover, the trackless-trolley bus can be built larger, and can operate at higher speeds than the battery bus, owing to the power equipment of the latter being limited by the size of the battery. These considerations, and others, indicate that the electric battery bus cannot compete successfully with the trackless-trolley bus.

When comparing the trackless-trolley system with the other alternative system of petrol-driven motor-buses, the former possesses the advantages of (1) lower running costs, (2) considerably lower maintenance and inspection costs, (3) longer life of vehicles and equipment, (4) simpler starting and speed control. Against these advantages there are the

* Comparative average costs of conduit and overhead systems are—

	Per Mile of Single Track.
Conduit system (including special work, pipe diversions, etc.) .	£17,000
Overhead system (including special work, pipe diversions, etc.).	9,300

It must be noted, however, that, in every system, the cost of construction varies greatly, according to the nature of the obstructions and the extent of special work.

† The overhead system is adopted in the Greater London area.

‡ The cost of laying double track for tramways is, approximately, £12,000 per mile of route; and the cost of the overhead equipment, including the feeders and ducts, is, approximately, £3700 per mile of route.

serious disadvantages that the trolley-bus is tied to a definite route, and that considerable investment is necessary for the overhead construction which must be erected before any service can be given. Moreover, with motor-buses, should any route prove unremunerative, the buses on that route may be withdrawn and transferred immediately to another route without incurring any sacrifice of capital or capital charges. But with trolley-buses the abandonment of any route involves the sacrifice of the capital invested in the overhead equipment, and, further, the transference of the vehicles to an alternative route is only possible when this route is equipped with overhead trolley wires.

Methods of supplying power to railway trains. These comprise (1) the overhead system, (2) the conductor rail system.

The **overhead system** must, obviously, be adopted when the trains are supplied at high voltage. Under these conditions heavy trains may be supplied through conductors of relatively small cross-section, and the collection of the current required by a heavy train can be performed satisfactorily by a collector of the sliding bow type. Overhead construction is universal for all alternating-current railways, and it is also adopted for direct-current railways operating at voltages above 1500 volts. In all these cases the track rails are utilized as the return conductor, so that with direct-current and single-phase systems only one overhead wire is required for each track.

The **conductor rail system** is adopted for heavy electric traction systems operating at voltages up to about 1200 volts, since, in these cases, large currents may be required by the trains. The power is supplied to the trains through high conductivity steel rails, which are supported on insulators parallel with the track rails and fed at suitable points from the generating station or from sub-stations. The current is conveyed from the conductor rails to the train equipment by means of collector shoes. In some cases the track rails are used as the return conductor, so that only one conductor rail is required.

Technical aspects of railway electrification. In this country electrification has been confined to the urban and suburban lines in the vicinity of our large cities (e.g. London, Liverpool, Newcastle, Manchester). In the United States of America and on the Continent electrification has been carried to trunk lines and also to freight lines operating in mountainous districts.

The chief difficulties in the way of electrification of our trunk lines are: first, the existence of the modern steam locomotive; and, second, the large cost of converting the lines from steam to electric operation. The modern steam locomotive in service on our trunk lines is capable of fulfilling all the requirements of the traffic department for fast passenger traffic. An electric locomotive capable of performing similar services could be built, but this locomotive would have to show marked economies in power consumption and operating expenses in order to warrant the large cost of the change-over. The case is entirely different with suburban railways. On these railways large numbers of passengers have to be transported daily over relatively short distances in competition, in many cases, with other methods of transportation. For the railway to

retain its traffic and create additional traffic, the passengers must be transported over a given distance in a much shorter time than that required by its competitors.

Now, the frequent starting and stopping of steam trains at stations spaced a short distance apart does not lead to economical operation,* and, moreover, it is impossible to obtain high schedule speeds unless exceptionally heavy locomotives are adopted. On the other hand, an electric train is capable of handling such a service economically at a schedule speed which will attract traffic. This schedule speed may be from 50 to 100 per cent higher than that corresponding to steam operation, the increase being due to the higher acceleration of the electric train. Since the electric train is capable of running the service at a higher schedule speed, it follows that the train miles which can be run with a given equipment in a given time are greater with electric service than with steam service. A given number of electric trains is therefore capable of dealing with a greater volume of traffic than the same number of steam trains with equal seating accommodation. The electric train has the additional advantage that it may be divided and run in sections during the periods of light traffic, thereby enabling a frequent service of trains to be maintained, leading to increased traffic during these periods.

Electric traction also forms a solution to the problem of relieving congestion at terminal stations. Thus the number of trains which can be got into and out of a terminus in a given time depends on the number of signal and train movements required. With electric trains consisting of motor-coaches, the number of signal and train movements required for a train entering and leaving a terminus is only one-fourth of the number required for a steam train. Now the number of trains which can be run over the tracks in a given time is limited by the terminal facilities. It is obviously more desirable to increase these facilities by adopting electric traction than by the alternative of carrying out the widening of the tracks and the extensions and additions to the station platforms, since the electric train service will, in most cases, lead to additional traffic, the revenue from which will go towards meeting the cost of electrification.

Electric traction also possesses advantages over steam traction for the handling of freight traffic, particularly on railways having heavy gradients and long tunnels. In deciding upon the system of electrification to be adopted for a railway with heavy gradients, consideration would naturally be given to those systems in which electric regenerative braking could be used. The trains descending the gradients would be braked electrically, so that, instead of the kinetic energy of the train being dissipated in the brake shoes and wheel tyres, it would be converted into electrical energy and returned to the supply system. Thus, in addition to the saving in the power consumption, the maintenance of the brake shoes, wheel tyres, and track rails would be reduced. The reduction in the latter items alone may be sufficient to cover a fair percentage of the costs of electrification.

* In this connection see Sir John Aspinall's Presidential Address to the Institution of Mechanical Engineers, *Proceedings of the Institution of Mechanical Engineers* (1909), pp. 423–488.

Systems of railway electrification. These comprise (1) the direct-current system, (2) the single-phase alternating-current system, (3) the three-phase alternating-current system, and (4) the composite single-phase three-phase, and single-phase direct-current systems.

In the **direct-current system** the energy required by the trains must be obtained from substations (except in the case of a very short railway where a direct supply from a direct-current generating station may be possible) which receive energy from a three-phase high-tension transmission system; as, with an extensive electrification, it is not commercially practicable to supply the railway directly from one or more direct-current generating stations. The substations must, therefore, contain converting plant, which will consist of transformers in conjunction with rotary converters, motor-generators, or mercury-arc rectifiers. For heavy and dense traffic on suburban railways the substations will have to be spaced about 2 to 3 miles apart, but for main-lines operating at high voltage (3000 volts) the distance apart of the substations will be between 10 and 20 miles. Considerable progress has been made in recent years in the development of automatic and unattended substations equipped with converting plant (rotary converters or mercury rectifiers), and where the conditions are favourable to the employment of these substations a considerable saving in the operating costs is possible.

The train equipments must be built for operation at the line voltage, but with voltages above 1500 volts two or more motors may be operated permanently in series, so that the terminal voltage per motor is limited to one half, or a smaller fraction, of the line voltage. The insulation of the motors, however, must be designed to withstand the full line voltage. The series type of motor is always employed.

In the **single-phase system** the energy required by the trains may be obtained directly, at high voltage, from a generating station when the extent of the electrification is within a radius of about 20 miles from the generating station. For longer distances the economic voltage for the power transmission system is higher than that which is desirable for the traction system, and therefore transformer substations become necessary.

As single-phase traction motors are inherently low voltage machines, a transformer must be carried on each train to supply the motors at suitable voltage. The motors are usually of the series type.

In the **three-phase system** the energy required by the trains may be obtained either directly from the generating station, or from transformer substations which receive energy from a high-tension transmission system. Since two trolley wires per track are necessary, the line voltage of the traction system has to be limited to values below the highest voltages employed for single-phase railways, and as the traction motors (which are of the induction, or constant-speed, type) can be built economically for operation at moderately-high voltages, the line voltage is usually chosen so that the motors may be supplied directly from the trolley wires. The induction type of motor is employed, as, at present, no variable-speed polyphase traction motor has been developed. The induction motor, however, possesses the merits of a high efficiency and of operating as a generator, when it is driven at speeds above the synchronous speed and is connected to the supply system. The motor equipment of a train can, therefore, be used for regenerative braking during the descent of

gradients, and the constant-speed characteristic of the motors limits the speed of the train to a definite value.

In the **composite systems** the energy is distributed in the form of single-phase current at high voltage, and is converted on the locomotives into either three-phase or direct current at low voltage for utilization in the traction motors ; a transformer and phase-converter being necessary in one case, and a motor generator in the other case, for the conversion. These systems, therefore, combine the advantages of high-voltage single-trolley wire distribution with efficient traction motors suitable for regenerative braking. Their development has been due to the inferiority of 25-cycle, single-phase motors, compared with three-phase and direct-current motors for regenerative braking on a large scale, and their present application is limited to mountain ranges having heavy mineral traffic.

Operating voltages. *Direct-current* urban and suburban electrifications in the vicinity of large cities have operating voltages between 600 and 750 volts. For the longer distance suburban services, however, a higher voltage, between 1000 and 1500 volts, is desirable. For main-line electrification, voltages of 1500 and 3000 volts are employed, and higher voltages will become possible with the further development of the high-voltage mercury-arc rectifier (which is the best form of converting apparatus for the distribution system at voltages above 3000 volts), as at present the operating voltage is limited by the substation converting plant rather than by the train equipment. Progress in this direction is being made steadily, and already, in Italy, a railway is operating at 4000 volts.

Single-phase railways have operating voltages between 6000 and 15,000 volts, and the frequency is either $16\frac{2}{3}$ or 25 cycles. The lower voltage and higher frequency (11,000 volts, 25 cycles) have usually been chosen for American single-phase railways, and the higher voltage and lower frequency (15,000 volts, $16\frac{2}{3}$ cycles) for Continental railways.

Three-phase railways have operating voltages between 3000 and 10,000 volts, the frequency being either $16\frac{2}{3}$ cycles or between 42 and 50 cycles. The extensive electrifications in Northern Italy have been carried out at voltages between 3000 and 3700 volts, and a frequency of $16\frac{2}{3}$ cycles ; but for the recent extensions into Central Italy, an operating voltage of 10,000 volts has been chosen, the frequency being between 42 and 50 cycles, according to the frequency of the supply network from which the power is obtained.

Comparison of systems of railway electrification. The **direct-current system** is the oldest of the systems of railway electrification. Its greatest application has been to urban and suburban services at operating voltages between 500 and 800 volts, the first installations being made in about 1890 in this country and a few years earlier in America.* Its application to long-distance main-line service required the development of high-voltage direct-current machines and control apparatus. This development started in America, and the first installation (at an operating voltage of 2400 volts) was made in 1913.

The early applications of the **three-phase system** were to Swiss mountain railways, and the first application to main-line railways (operating

* The pioneer developments in the direct-current system of electric traction started about five years earlier, when electric tramways commenced operation, the overhead-trolley system and an operating voltage of 500 volts being employed.

at 3000 volts) was in 1902. Subsequent developments of the three-phase system have been entirely for main-line electrification, and the principal applications are in Northern Italy.

The **single-phase system** is of recent development, as the development of a suitable single-phase traction motor was necessary. The system has received its greatest development on the Continent (although much pioneer work was done in America), and extensive applications of the system are to be found in Switzerland, Germany and Scandinavia on suburban as well as main-line railways.

The **composite systems** are of later development, and were introduced to overcome the disadvantages of the straight single-phase system for heavy mineral traffic on mountain grades. They must, therefore, be considered as entirely special systems of electrification, applicable only to exceptional operating conditions. Any future installations, however, will probably be of the single-phase, direct-current form (with motor-generators and direct-current motors on the locomotives instead of phase-converters and three-phase motors as installed formerly), owing to the advantages possessed by this system over the single-phase three-phase system for speed control.

As there appears to be no tendency towards the development or application of the three-phase system to new electrifications (other than extensions of existing electrifications)—due to the complicated nature of the overhead construction and the low frequency—the systems available for any new electrification are (1) the direct-current system and (2) the single-phase system.

For **heavy suburban service** the low-voltage direct-current system is undoubtedly superior to the single-phase system, as the following comparison will show—

The dynamical characteristics of the direct-current traction motor are better suited for the frequent and rapid acceleration of heavy trains than those of the single-phase traction motor.

The direct-current train equipments are lighter, more efficient, and less costly (both initially and in maintenance) than corresponding single-phase equipments. Moreover, the energy consumption of a direct-current train will be lower than that of a single-phase train operating under similar service conditions.

The conductor-rail distribution system will be less costly, both initially and in maintenance, than the high-voltage overhead distribution system.

The direct-current system causes no interference with neighbouring overhead communication (telephone) circuits. This interference may be serious with the single-phase system, and may necessitate placing the communication circuits either along another route or underground. Moreover, due to the high impedance of the track rails, when used as conductors for alternating current, special arrangements (involving transformers and insulated cables) are necessary with the single-phase system to relieve the track rails of the return current, and so avoid troubles due to earth currents (such currents affecting telegraph and other weak-current circuits using the earth as a return).

These advantages of the direct-current system will generally more than compensate for the chief disadvantage of this system, viz. the

necessity for converting substations at relatively short distances apart. The cost of the substations, however, must not be placed wholly against the direct-current system, as, in the single-phase system, switch cabins —spaced at approximately the same distances apart as the substations in the direct-current system—must be provided for the switchgear which is necessary for the sectionalization and feeding of the trolley wires.

Lastly, if the single-phase system is supplied directly from a thermal generating station, both the cost of the generators and the steam consumption will be higher (due to the abnormally low frequency) than those of a similar station equipped with three-phase generators of standard (50) frequency and supplying substations containing converting machinery.

For **main-line long distance services,** however, both high-voltage direct-current and single-phase systems are capable of giving satisfactory results. The single-phase system appears to possess advantages over the direct-current system for long-distance electrification, on account of the higher line voltage and the apparent simplicity of the transmission and distribution arrangements. But with the development of the unattended substation with mercury rectifiers and the use of high voltages in the direct-current system, these advantages will not be so apparent, particularly when provision has to be made (in the single-phase system) for the prevention of interference with neighbouring communication circuits. Moreover, it will generally be advantageous to the railway company either to arrange to supply industrial districts from its own generating station (for the purpose of improving the load factor on the generating station and thereby effecting economics in the operation of the plant), or to purchase its energy from a large industrial power supply system. In both cases substations containing rotating machinery (synchronous motor-alternator sets) will be necessary for a single-phase traction system.

Further points of comparison between the high-voltage direct-current and single-phase systems for long-distance electrification are—

The characteristics of the single-phase traction motor are more suitable for the conditions of main-line service than those of the present direct-current traction motor, and with single-phase equipment a greater number of efficient operating speeds are available than can be provided with a direct-current equipment.

Single-phase locomotives are more expensive initially than direct-current locomotives ; their efficiency is lower and their maintenance costs are higher than those of direct-current locomotives.

Regenerative braking can be obtained more efficiently, and with less complication, and less additional equipment, with the direct-current system than with the single-phase system.

The cost of the overhead distribution systems may not differ appreciably in the two cases.

In Table I are given data of a number of electric railways in this country and abroad. The extent of the practical application of the above systems of electrification can be seen from this table.

The **generation of electrical energy** and its distribution is a business in itself. In many cases it is desirable for the railway company to purchase power, since the company is thereby relieved not only of the initial cost of the generating station and the capital charges thereon,

but also of the management of a business organization which is very different from its other organizations. In the United States of America the purchase of power for railway electrification from the large electric power supply companies is carried out on an extensive scale; but in this country, owing to the limited number of large power supply companies and their distance, in many cases, from the area of electrification, there are only two examples of the purchase of power for railway electrification—viz. the London and North Eastern Railway (which purchases power for its Newcastle-Tynemouth and Newport-Shildon branches from the North-East Coast power supply companies) and the Southern Railway (which purchases power for its Eastern section from the London Power Co.).*

As the subject of the generation of electrical energy is one of considerable magnitude at the present day, and has little bearing on the utilization of the energy for traction purposes, we shall not consider the equipment of the generating station. The equipment of the substations, however, is considered in detail, since, when power is purchased, the substations would generally (although not necessarily) be under the control of the railway company.

NOTE.—The following papers contain much information on railway electrification under British conditions—

"The Electrification of Suburban Railways" (F. W. Carter), *Proceedings of the Institution of Mechanical Engineers* (1910), p. 1073.

"The Cost of Electrically-propelled Suburban Trains" (H. M. Hobart), *ibid*, p. 1103.

"The Equipment and Working Results of the Mersey Railway under Steam and under Electric Traction" (J. Shaw), *Minutes of Proceedings of the Institution of Civil Engineers*, vol. 179, p. 19.

"Some Railway Conditions governing Electrification" (Roger T. Smith), *Journal of the Institution of Electrical Engineers*, vol. 52, p. 293.

"Electrification of Railways as affected by Traffic Considerations" (H. W. Firth), *ibid*, p. 609.

"The Future of Main-line Electrification" (H. E. O'Brien), *ibid* vol., 62, p. 729.

* Formerly, the London, Brighton and South Coast Railway purchased power for their suburban lines (a portion of which was electrified, on the single-phase system, in 1908, and the electrification of the suburban system was completed in about 19[illegible]) from the London Electric Supply Corporation, Deptford. With the inclusion of this railway in the Southern group these lines are being converted to direct-current working so as to obtain uniformity in the whole of the Southern suburban system.

CHAPTER II

THE MECHANICS OF TRAIN MOVEMENT

I. Preliminary Study of Speed-time Curves

The motion of a train or any vehicle is made up of periods of acceleration, of retardation, and, in some cases, of constant speed. Now, acceleration and retardation represent the rate of change of speed with respect to time; therefore, a curve which shows the speed of the train with respect to time will also supply information concerning the acceleration and retardation. For example, the acceleration or retardation at any instant can be obtained by determining the tangent of the angle of inclination of this curve (at the given instant) to the time axis—an upward slope (tangent positive) indicating acceleration, and a downward slope (tangent negative) indicating retardation. The acceleration, or retardation, obtained by this method will be given in terms of the units adopted for the axes of speed and time. If the former is represented in miles per hour and the latter in seconds, the acceleration or retardation will be expressed in miles per hour per second (abbreviated, ml.p.h.p.s.).*

Further, the distance travelled by the train during a given interval of time can be obtained by determining the area between the curve and the time axis corresponding to this interval.

It is apparent, therefore, that curves of the above type (which are called "**speed-time**" **curves**) are of considerable importance in connection with the movement of trains. But in electric traction these curves are of *fundamental importance*, since, if we are also provided with the characteristic curves of the driving motors, we can calculate the energy consumed by the train during the run. Moreover, with a knowledge of the resistances to motion, we are able to *estimate* the energy required to operate a train to a given schedule, as soon as the speed-time curve, corresponding to this schedule, has been determined.

It is necessary, therefore, to consider in detail the various portions of the speed-time curve, and to show how the curve corresponding to a given schedule may be obtained.

A speed-time curve, for a run between two stations, is usually made up of periods of (1) acceleration; (2) constant speed, or "free running" (which may be zero for short distance runs); (3) coasting, i.e. running with power shut off, the retardation being due to the resistances to motion; and (4) retardation or braking.

With electric trains, equipped with series motors, the period of acceleration is made up of (*a*) an initial period, during which the acceleration is practically constant; followed by (*b*) a period in which the acceleration gradually decreases until the maximum speed is reached.

The period of constant acceleration corresponds to the "notching" or starting period, during which the current input to the motors can be

* In this treatise we shall generally express acceleration in this manner, since speeds, in tramway and railway calculations, are usually expressed in miles per hour. It is useful to remember that an acceleration of one mile per hour per second is equivalent to 1·466 feet per second per second.

maintained at a definite mean value. This value depends on the number of notches, the grading of the rheostats, and the rate at which the rheostats are cut out.

When full voltage is applied to the motors, the current and torque will decrease as the speed increases. Therefore the acceleration will gradually decrease until the torque is just sufficient to balance the resistances to motion. The shape of this portion of the speed-time curve will depend entirely on the shape of the speed-torque curve of the motor, and will be affected to some extent by variations in the line voltage and in the resistances to motion.

These two portions of the accelerating period are called respectively "**rheostatic acceleration**" or "acceleration while notching," and "acceleration on the speed curve" or "**speed-curve running.**"

The duration of the free-running and coasting periods will depend on the nature of the service (that is, the distance between the stops and the average speed between the stations), and will be affected by the acceleration and retardation, as discussed below.

Typical speed-time curves for electric trains operating on passenger services are given in Figs. 1, 2, 3. Each curve corresponds to a particular class of traffic, viz. (1) urban or city service, where the distance between stops is of the order of 0·5 mile; (2) suburban service, where the distance between the stops may average from 1·5 to 2 miles over a distance of from 15 to 20 miles from the city terminus; (3) main-line service, where the stops are infrequent.

In Fig. 1, which is representative of city service, relatively high values must be adopted for the acceleration and retardation in order to obtain a moderately high average speed between the stations. The short distance between the stations does not permit of a free-running period. since it is desirable to include a short coasting period in order to obtain a reasonable energy consumption. This class of traffic requires a frequent service of trains.

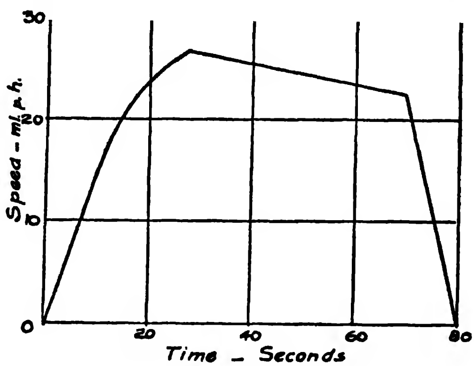


FIG. 1.—Speed-time Curve for City Service.

In suburban service (Fig. 2) the longer distance between the stations permits of a free-running period and a longer coasting period than is possible with city service. In this case, also, relatively high values for the acceleration and retardation are required in order to render the service as attractive as possible. Moreover, at certain periods in the day there will be a large traffic in one direction, which will require a frequent service of trains during these periods.

Main-line service (Fig. 3) is characterized by the long periods of free-running at high speeds, the accelerating period being relatively unimportant.

It is apparent, therefore, that the requirements for urban and main-line services are totally dissimilar, hence an equipment designed for main-line service will be totally unsuited for urban service, and vice versa. The full discussion of this point, however, must be deferred until later.

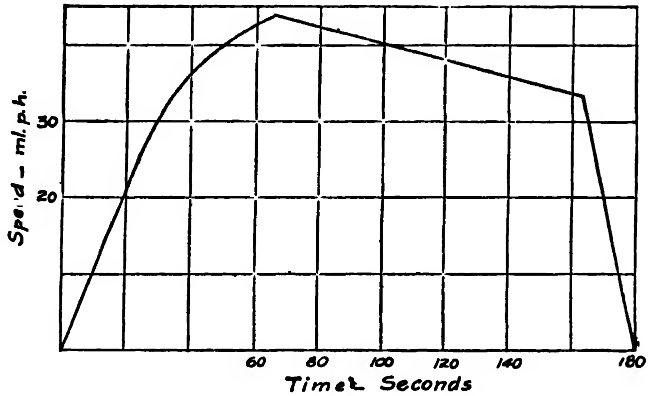


FIG. 2.—Speed-time Curve for Suburban Service.

The **initial acceleration** for electric trains is from 1·0 to 1·5 miles per hour per second. These values are from two to three times those obtained with the ordinary class of steam locomotive.

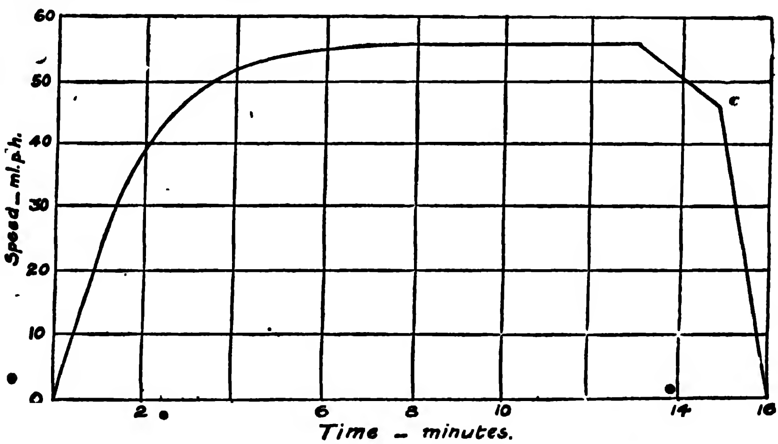


FIG. 3.—Speed-time Curve for Main-line Service.

The **limitations to the acceleration** are (1) the weight of the equipment; (2) the peak load on the substations and power house; (3) the discomfort of the passengers; while, in addition, there are financial considerations, such as (4) the cost of the rolling stock and equipment; (5) the maintenance charges on the equipment and rolling stock; (6) the cost of energy.

ERRATA

Page 13, Fig. 4 (c). For β_c *read* $\tan^{-1}\beta_c$.

Page 113, fourth line from foot of page. For Fig. 65A *read* Fig. 65.

Page 114, third line from top of page. For Fig. 65B *read* Fig. 65A.

Page 593, foot of page. For $E = 0{\cdot}8\,V^2/R$ *read* $E = 3{\cdot}8\,V^2/R$.

Page 698, centre of page. For $+$ 3 per cent *read* $\pm$ 3 per cent.

Page 710, answers to Ex. VI, 2 *should read* 6·8″, 1·3 : 1.

(5043)

Braking retardation. With the adoption of a high acceleration it becomes necessary to employ a high retardation, in order to obtain a reasonable energy consumption, since, for given values of acceleration, distance of run, and average speed, the higher the retardation the longer will be the coasting period,* and, therefore, the shorter the time during which power is supplied to the motors. With modern types of quick-acting brakes, a retardation up to 3½ miles per hour per second can be obtained. For urban and suburban services at high schedule speeds the retardation during braking is from 2·0 to 2·5 miles per hour per second.

Simplified speed-time curve. When comparative performances for a given service, at various schedule speeds,† are required (for example, in preliminary calculations for time-tables, etc.), the actual speed-time curves of Figs. 1, 2, 3 are replaced by simplified speed-time curves, which do not involve a knowledge of the motor characteristic. These simplified

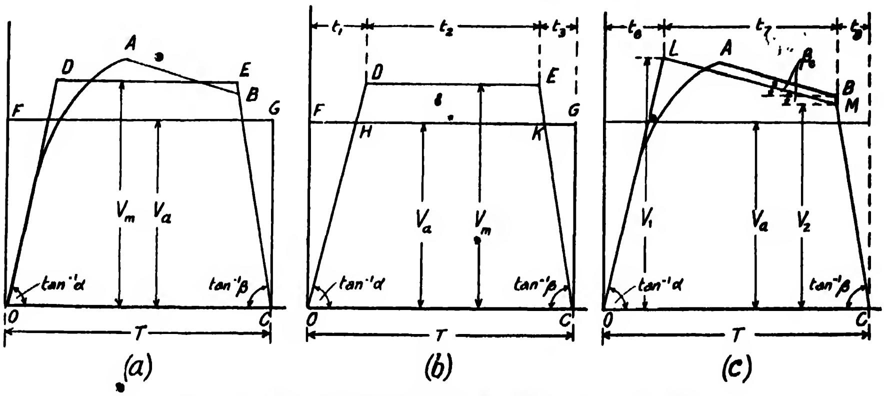


FIG. 4.—Methods of Simplifying Speed-time Curves for Preliminary Calculations.

speed-time curves have simple geometric shapes, and, in consequence, the relationship between the acceleration, retardation, average speed, and distance can be deduced by simple mathematics.

For example, the speed-time curve of Fig. 1 can be replaced by either of the equivalent quadrilateral diagrams shown in Fig. 4, in both of which the acceleration and braking retardation have the same values as those in Fig. 1, and all diagrams enclose the same area. The speed-curve-running and coasting periods of the actual speed-time curve, Fig. 1, are replaced in one case, Fig. 4 (*a*), by a constant-speed period, and in the other case, Fig. 4 (*c*), by extensions of the initial accelerating and coasting periods.

The trapezoidal diagram, Fig. 4 (*a*), gives the simpler relationship between the principal quantities concerned with speed-time diagrams, and also gives a close approximation to the actual energy required for propulsion on long distance runs on level track. On the other hand, the

* With a given distance between stops, the running time and the area of the speed-time diagram must be constant.

† Schedule, or "booked," speed is the average speed obtained when the duration of the stop is included.

quadrilateral diagram, Fig. 4 (*c*), approximates more closely to the actual conditions on short-distance runs in which coasting is an important item.

Relationship between principal quantities in speed-time curves. Considering the **trapezoidal speed-time curve,** Fig. 4 (*b*), let

D = distance between stops, in miles.
T = running time, in seconds.
α = acceleration, in miles per hour per second.
β = retardation, in the same units.
V_a = average speed, in miles per hour ($= 3600D/T$).
V_m = free-running, or maximum, speed, in miles per hour.
t_1 = time of acceleration, in seconds ($= V_m/\alpha$).
t_3 = time of braking, in seconds ($= V_m/\beta$).
t_2 = time of free running, in seconds [$= T - (t_1 + t_3)$].

Then the area of the trapezium—which represents the distance between stops—is given by*

$$\begin{aligned} D &= V_m(\tfrac{1}{2}t_1 + t_2 + \tfrac{1}{2}t_3)/3600 \\ &= V_m[\tfrac{1}{2}(t_1 + t_3) + T - (t_1 + t_3)]/3600 \\ &= V_m[T - \tfrac{1}{2}(t_1 + t_3)]/3600 \end{aligned}$$

Substituting for t_1 and t_3 in terms of V_m, α, β, we have

$$D = \frac{1}{3600}\left\{ V_m T - \tfrac{1}{2}V_m^2\left(\frac{1}{\alpha} + \frac{1}{\beta}\right)\right\} \quad . \quad . \quad . \quad . \quad (1)$$

When α or β is to be determined we re-arrange this equation in the form

$$\frac{1}{\alpha} + \frac{1}{\beta} = \frac{7200}{V_m^2}\left(\frac{V_m T}{3600} - D\right)$$

or, since $T/3600 = D/V_a$, we have

$$\frac{1}{\alpha} + \frac{1}{\beta} = \frac{7200D}{V_m^2}\left(\frac{V_m}{V_a} - 1\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

When V_m is to be determined, equation (1) is re-arranged as an ordinary quadratic equation, thus

$$\left[\frac{1}{7200}\left(\frac{1}{\alpha} + \frac{1}{\beta}\right)\right] - V_m\left(\frac{T}{3600}\right) + D = 0$$

and the solution is obtained by general algebraic rules. For example, in the case of an equation of the form $ax^2 + bx + c = 0$, the solution is given by

$$x = \frac{-b \pm \sqrt{(b^2 - 4ac)}}{2a} \text{ or } x = -\frac{b}{2a} \pm \sqrt{\left[\left(\frac{b}{2a}\right)^2 - \left(\frac{c}{a}\right)\right]}$$

Hence, in the present case, where

$$x = V_m,\ a = \frac{1}{7200}\left(\frac{1}{\alpha} + \frac{1}{\beta}\right),\ b = -\frac{T}{3600},\ c = D, \text{ we have}$$

$$V_m = \left(\frac{\alpha\beta}{\alpha + \beta}\right) T - \sqrt{\left[\left(\frac{\alpha\beta}{\alpha + \beta}\right)^2 T^2 - 7200D\left(\frac{\alpha\beta}{\alpha + \beta}\right)\right]} \quad . \quad . \quad (3)$$

* **For the area to represent distance in miles, ordinates (i.e. speed) must be expressed in miles per hour and abscissae (i.e. time) in hours.**

The numerical evaluation of this equation is effected expeditiously by the use of the slide rule, but it becomes tedious when ordinary arithmetic is employed. An *alternative equation* for V_m, which avoids the extraction of a square root, is readily derived from the geometry of Fig. 4 (*b*). Thus, since the trapezium *ODEC* and the equivalent rectangle *OFGC* are of equal area, the area of the smaller trapezium *HDEK* must be equal to the combined area of the two triangles *OFH*, *KGC*. If the periods *FH*, *KG* are denoted by t_4, t_5, respectively, the equality of these areas is given by

$$\tfrac{1}{2}(V_m - V_a)[t_2 + T - (t_4 + t_5)] = \tfrac{1}{2}V_a t_4 + \tfrac{1}{2}V_a t_5$$

Now $t_1 = V_m/a$, $t_3 = V_m/\beta$, $t_4 = V_a/a$, $t_5 = V_a/\beta$.

Hence, substituting for these quantities and re-arranging terms we have

$$(V_m - V_a)\left\{T - \left(\frac{1}{a} + \frac{1}{\beta}\right)\left[V_a + \tfrac{1}{2}(V_m + V_a)\right]\right\} = \tfrac{1}{2}V_a^2\left(\frac{1}{a} + \frac{1}{\beta}\right)$$

and, finally,

$$V_m = V_a + \frac{\tfrac{1}{2}V_a^2(a + \beta)/a\beta}{T - \tfrac{1}{2}(V_m + V_a)(a + \beta)/a\beta}$$

$$= V_a + \frac{\tfrac{1}{2}V_a^2(a + \beta)/a\beta}{T - \tfrac{1}{2}V_a(1 + V_m/V_a)(a + \beta)/a\beta} \quad . \quad . \quad . \quad (3a)$$

The evaluation of this equation requires a knowledge of the value of the ratio V_m/V_a (which depends upon the shape of the trapezium *ODEC*). But for speed-time curves of the shapes of Figs. 1 and 2 sufficient accuracy will usually be obtained by assuming V_m/V_a as 1·25. The correctness of the assumption can always be checked from the separate values of V_m and V_a derived by calculation, and, if necessary, a closer degree of accuracy may be obtained by a further calculation of V_m [from equation (3*a*)] using a revised value for V_m/V_a.

Considering the **quadrilateral speed-time curve,** Fig. 4 (*c*), let V_1, V_2, denote the speeds—in miles per hour—at the beginning and end, respectively, of the coasting period, t_7, the duration, in seconds, of this period; t_6, t_8, the duration, in seconds, of the accelerating and braking periods, respectively; β_c the coasting retardation in ml.p.h.p.s.; and *D*, *T*, *a*, *β*, V_a refer to the same quantities as employed in the trapezoidal speed-time curve. Then the area of the quadrilateral *OLMC* is given by

$$D = [\tfrac{1}{2}V_1(t_6 + t_7) + \tfrac{1}{2}V_2(t_7 + t_8)]/3600$$
$$= [\tfrac{1}{2}V_1(T - t_8) + \tfrac{1}{2}V_2(T - t_6)]/3600$$
$$= \left[\tfrac{1}{2}T(V_1 + V_2) - \tfrac{1}{2}V_1V_2\left(\frac{1}{a} + \frac{1}{\beta}\right)\right]/3600$$

Now $V_2 = V_1 - \beta_c t_7 = V_1 - \beta_c[T - (t_6 + t_8)]$
$$= V_1 - \beta_c T + V_1\beta_c/a + V_2\beta_c/\beta$$

i.e. $V_2 = \beta[V_1(1 + \beta_c/a) - \beta_c T]/(\beta - \beta_c)$ . . . . . (4)

Substituting this value for V_2 in the equation for *D* and simplifying, we obtain

$$D = \frac{1}{7200}\left\{V_1 T\left[1 + \frac{a(\beta + \beta_c) + 2\beta\beta_c}{a(\beta - \beta_c)}\right]\right.$$
$$\left.\frac{\beta}{\beta - \beta_c}\left[V_1^2\frac{(a + \beta_c)(a + \beta)}{a^2\beta} + \beta_c T^2\right]\right\} \quad . \quad . \quad . \quad (5)$$

and by further simplification and re-arrangement we have

$$a^2\left[7200\frac{D}{V_1}(\beta-\beta_c)-T\beta\left(2-\frac{T\beta_c}{V_1}\right)+V_1\right]$$
$$+a\left[V_1(\beta+\beta_c)-2\beta\beta_cT\right]+V_1\beta\beta_c=0 \quad . \quad . \quad . \quad (6)$$

In the application of these equations β, β_c, D and the average speed (from which T can be calculated) will usually be known. Solutions can then be obtained for V_1 when a is given, or for a when V_1 is given. V_2 is then obtained from the equation

$$V_2 = [V_1(1+\beta_c/a)-\beta_cT]\,\beta/(\beta-\beta_c)$$

If, however, the distance, D, is required, when values of the acceleration, retardations, and the duration of these periods are given, the calculation is more straightforward when carried through step by step (as in Example 3, below) rather than by substituting in equation (5).

Examples. (1) A train runs on a service in which there are two stops per mile and the schedule speed is 17 ml.p.h., stops being of 20 seconds' duration. Determine the trapezoidal speed-time curve for the run if the acceleration is 1·2 ml.p.h.p.s. and the braking retardation is 2 ml.p.h.p.s.

The distance between stops (D) is 0·5 mile. Whence the schedule time is ($3600 \times 0{\cdot}5/17 =$)105·8 sec. and the running time (T) is ($105{\cdot}8-20=$)85·8 sec.

Hence, substituting in equation (3) and solving for V_m we obtain

$$V_m = 26{\cdot}4 \text{ ml.p.h.}$$

Also $\quad V_a = 3600\,D/T = 3600 \times 0{\cdot}5/85{\cdot}8 = 20{\cdot}97$ ml.p.h.

Whence

t_1 = duration of accelerating period $= V_m/a = 22$ sec.
t_3 = duration of braking period $= V_m/\beta = 13{\cdot}2$ sec.
t_2 = duration of free-running period $= T-(t_1+t_3) = 50{\cdot}6$ sec.
D_1 = distance run during accelerating period $= \frac{1}{2}V_mt_1/3600 = 0{\cdot}0806$ ml.
D_2 = distance run during free-running period $= V_mt_2/3600 = 0{\cdot}371$ ml.
D_3 = distance run during braking period $= \frac{1}{2}V_mt_3/3600 = 0{\cdot}0484$ ml.

(2) A train is required to run between stations 1 mile apart at a schedule peed of 25 ml.p.h., the duration of the stops being 20 seconds. The braking retardation is 2·25 ml.p.h.p.s. Assuming a trapezoidal speed-time curve, calculate the acceleration if the ratio (maximum speed/average speed) is to be 1·25.

The schedule time is ($1 \times 3600/25 =$) 144 sec.

Hence the running time (T) is $(144-20) = 124$ sec., and the average speed (V_a) is ($1 \times 3600/124 =$) 29·05 ml.p.h.

Whence the maximum speed (V_m) $= 1{\cdot}25 \times 29{\cdot}05 = 36{\cdot}3$ ml.p.h.

The acceleration is calculated from equation (2) thus

$$\frac{1}{a}=\frac{7200D}{V_m^2}\left(\frac{V_m}{V_a}-1\right)-\frac{1}{\beta}$$

i.e. $$\frac{1}{a}=\frac{7200\times 1}{36{\cdot}3^2}(1{\cdot}25-1)-\frac{1}{2{\cdot}25}=0{\cdot}917$$

and $\quad a = 1{\cdot}09$ ml.p.h.p.s.

(3) A train is accelerated uniformly from rest until a speed of 25 ml.p.h. is reached 20 seconds after starting. Power is then cut off and the train coasts for 40 seconds. The brakes are then applied and the train is brought to rest 70 seconds after starting. The retardation during coasting may be assumed to be uniform at the rate of 0·1 ml.p.h.p.s. Determine the distance run from start to stop and the average speed.

The calculation is best effected step by step. First the speed (V_2) at the end of the coasting period is determined. Thus

$$V_2 = V_1 - \beta_c t_7 \text{ (p. 15)} = 25 - 0{\cdot}1 \times 40 = 21 \text{ ml.p.h.}$$

Hence,

Distance run during accelerating period $= \frac{1}{2} \times 25 \times 20/3600 \quad = 0{\cdot}0694$ ml.
Distance run during coasting period $= \frac{1}{2}(25 + 21) \times 40/3600 = 0{\cdot}2555$ ml.
Distance run during braking period $= \frac{1}{2} \times 21 \times 10/3600 \quad = 0{\cdot}0292$ ml.

$\therefore$ total distance run $= 0{\cdot}354$ ml.

Whence average speed $= 0{\cdot}354 \times 3600/70 = 18{\cdot}2$ ml.p.h.

(4) A train is required to run between stations 1·2 miles apart at a schedule speed of 25 ml.p.h., the duration of the stops being 20 seconds. The run is to be made according to a quadrilateral speed-time curve, Fig. 4 (c), and the coasting and braking retardations may be assumed at 0·1 ml.p.h.p.s. and 2 ml.p.h.p.s. respectively. Determine the acceleration if the speed at the end of the accelerating period is 38 ml.p.h. Determine also the duration of the coasting period.

The schedule time is ($1{\cdot}2 \times 3600/25 =$) 172·7 sec., and the running time (T) is ($172{\cdot}7 - 20 =$) 152·7 sec.

The acceleration is calculated from equation (6) by substituting the appropriate numerical values for D, V_1, T, β, β_c. Thus, after substitution and simplification, we obtain the equation

$$-18a^2 + 18{\cdot}72a + 7{\cdot}6 = 0$$

from which $\qquad a = 1{\cdot}352$ ml.p.h.p.s.

Hence, duration of accelerating period $= 38/1{\cdot}352 = 28{\cdot}1$ sec.

The duration of the coasting period can be determined when the speed (V_2) at the end of this period is known. This speed is calculated from equation (4), thus

$$\begin{aligned} V_2 &= \beta[V_1(1 + \beta_c/a) - \beta_c T]/(\beta - \beta_c) \\ &= 2[38(1 + 0{\cdot}1/1{\cdot}352) - 0{\cdot}1 \times 152{\cdot}7]/1{\cdot}9 \\ &= 26{\cdot}88 \text{ ml.p.h.} \end{aligned}$$

Whence duration of coasting period

$$= t_7 = (V_1 - V_2)/\beta_c = (38 - 26{\cdot}88)/0{\cdot}1 = 111{\cdot}2 \text{ sec.}$$

A check upon the calculations can be made by calculating (1) the braking retardation from V_2 and the duration of the braking period; (2) the distances run during acceleration, coasting, and braking.

Thus, the duration of the braking period

$$= 152{\cdot}7 - (28{\cdot}1 + 111{\cdot}2) = 13{\cdot}4 \text{ sec.}$$

and the computed braking retardation is $26{\cdot}88/13{\cdot}4 = 2{\cdot}005$ ml.p.h.p.s., which checks closely with the given value of 2·0 ml.p.h.p.s.

Distance run during acceleration $= \frac{1}{2} \times 38 \times 28{\cdot}1/3600 \quad = 0{\cdot}148$ ml.
Distance run during coasting $= \frac{1}{2}(38 + 26{\cdot}88) \times 111{\cdot}2/3600 = 1{\cdot}002$ ml.
Distance run during braking $= \frac{1}{2} \times 26{\cdot}88 \times 13{\cdot}4/3600 \quad = 0{\cdot}05$ ml.

Whence the total computed distance $= 0{\cdot}148 + 1{\cdot}002 + 0{\cdot}05 = 1{\cdot}2$ ml., which is correct.

(5) A train is required to run between stations 1 mile apart at an average speed of 25 miles per hour. The run is to be made to a quadrilateral speed-time curve, the acceleration being 1·25 ml.p.h.p.s. and the coasting and braking retardations being 0·1 and 2 ml.p.h.p.s. respectively. Determine the duration of the accelerating, coasting, and braking periods and the distances run during these periods.

In this problem the speeds V_1, V_2, at the beginning and end, respectively,

of the coasting period must first be determined, V_1 being calculated from equation (5), and V_2 from equation (4).

The running time $(T) = 1 \times 3600/25 = 144$ sec.

Hence, substituting this value and the known values of D, a, β, β_c in equation (5) and simplifying, we obtain the equation for V_1 as

$$1{\cdot}476\,V_1^2 - 327{\cdot}3V_1 + 9382 = 0$$

Whence $\quad V_1 = 33{\cdot}96$ ml.p.h.

Substituting in equation (4), we obtain

$$V_2 = 23{\cdot}45 \text{ ml.p.h.}$$

Hence,

Duration of accelerating period $= V_1/a = 27{\cdot}17$ sec.
Duration of coasting period $= (V_1 - V_2)/\beta_c = 105{\cdot}1$ sec.
Duration of braking period $= V_2/\beta = 11{\cdot}73$ sec.
Distance run during accelerating period $= \frac{1}{2} \times 33{\cdot}96 \times 27{\cdot}17/3600$
$= 0{\cdot}128$ ml.
Distance run during coasting period $= \frac{1}{2}(33{\cdot}96 + 23{\cdot}45) \times 108/3600$
$= 0{\cdot}837$ ml.
Distance run during braking period $= \frac{1}{2} \times 23{\cdot}45 \times 11{\cdot}73/3600$
$= 0{\cdot}0382$ ml.

Total computed distance $= 0{\cdot}128 + 0{\cdot}837 + 0{\cdot}0382 = 1{\cdot}003$ ml.

[NOTE.—The slight discrepancy between the computed distance (1·003 ml.) and the actual distance (1·0 ml.) is due to the use of the slide rule in making the calculations.]

Equivalent speed-time curve. An important property of speed-time curves of constant shape, but of unequal area, is that they can all be reduced to an equivalent speed-time curve of the same shape, provided that the co-ordinates of this equivalent speed-time curve are suitably chosen. Thus, consider two trapezoidal speed-time curves A, B, of similar shape but of unequal area, plotted to the same co-ordinates. Let the maximum ordinate of B be k times that of A. Then, since the shape is constant in the two cases, the acceleration and the braking retardation must remain constant, and the durations of the accelerating, braking, and free-running periods of speed-time curve B must be k times those of the corresponding periods of speed-time curve A. Consequently, the area of speed-time curve B—which represents the distance run, say D_2 miles—is k^2 times that of speed-time A (which refers to a run of, say, D_1 miles). That is, $D_2 = k^2D_1$, or $k = \sqrt{(D_2/D_1)} = \sqrt{(s_1/s_2)}$, where s_1, s_2 are the reciprocals of the distances D_1, D_2 respectively, and denote the *stops per mile* corresponding to services run according to the speed-time curves A and B, respectively.

Hence if T_1, T_2, denote the running times, and V_{1m}, V_{2m}, the maximum speeds in the two cases, A and B, respectively, then

$$T_2 = kT_1 = T_1\sqrt{(s_1/s_2)}, \text{ or } T_2\sqrt{s_2} = T_1\sqrt{s_1}$$

and $$V_{2m} = kV_{1m} = V_{1m}\sqrt{(s_1/s_2)}, \text{ or } V_{2m}\sqrt{s_2} = V_{1m}\sqrt{s_1}$$

Therefore, if the co-ordinates of the original speed-time curves are changed to speed × √(stops per mile) and time × √(stops per mile), a single speed-time curve will be obtained.

The equivalent speed-time curve is of considerable use in estimations of energy consumption, and its application is discussed in the next chapter.

Factors affecting schedule speed. The schedule speed of a given train when running on a given service (i.e. with a given distance between stations) is influenced by the duration of the stop, the acceleration, the braking retardation, and the maximum speed. With different classes of service the distance between stops has also a considerable influence on the schedule speed. In order to show the effect, on the schedule speed, of these variables, the Tables II, III, IV, and the curves in Figs. 5, 6, 7, have been prepared. The trapezoidal form of speed-time curve, Fig. 4(*b*), has been employed for the calculations for Tables III and IV.

The **effect of the duration of the stop** on the schedule speed, for a given average speed, is shown in Table II, which emphasizes the importance of short stops for urban service. For this class of service a stop of 15 to 20 seconds' duration is generally sufficient. The effect of increasing the stop (in Table II) from 10 to 20 seconds reduces the schedule speed by 10 per cent; and if the stop is increased to 40 seconds, the schedule speed will be 16·4 per cent less than that with a stop of 20 seconds. With longer distances between stations, the duration of the stop can be increased without affecting the schedule speed to any great extent. Thus, comparing the 2 mile and 5 mile runs, the effect of increasing the duration of stop from 20 to 40 seconds reduces the schedule speeds by 5·4 per cent and 2·4 per cent respectively.

TABLE II

SCHEDULE SPEEDS CORRESPONDING TO AN AVERAGE SPEED OF 22 ML.P.H. FOR VARIOUS DISTANCES BETWEEN STOPS AND DURATION OF STOP.

Distance between stops:	0·5 mile	1·0 mile		5 miles
Duration of Stop.		SCHEDULE SPEED.		
seconds.	ml.p.h.	ml.p.h.	ml.p.h.	ml.p.h.
10	19·6	20·8	21·3	21·7
20	17·7	19·6	20·7	21·4
30	16·1	18·6	20·1	21·2
40	14·8	17·7	19·6	20·9
50	13·7	16·9	19·1	20·7
60	12·7	16·1	18·6	20·5

Table III gives the **minimum acceleration** required to maintain various schedule speeds under various conditions. The rate of braking has been taken at 2·0 ml.p.h.p.s. in all cases, and the maximum speed from 20 per cent to 40 per cent above the average speed, depending on the distance between stops. This gives conditions which are similar to those encountered in practice, since, the longer the distance between stops, the lower will be the ratio between maximum and average speeds. The method by which the figures, in the last column of Table III, have been obtained is the same as that employed in Example (2), p. 16. Thus

TABLE III

MINIMUM ACCELERATION REQUIRED FOR VARIOUS SERVICES.
BRAKING RETARDATION : 2·0 ML.P.H P.S.

Distance between Stops.	Duration of Stop.	Schedule Speed.	Schedule Time.	Running Time.	Average Speed.	Ratio :— Maximum Speed / Average Speed	Maximum Speed.	Minimum Accelera-tion.
miles.	seconds.	ml.p.h.	seconds.	seconds.	ml.p.h.		ml.p.h.	ml.p.h.p.s.
0·5	10	15	120	110	16·36	1·4	22·9	0·45
		20	90	80	22·5		31·5	1·05
		25	72	62	29		40·6	2·68
	20	15	120	100	18	1·4	25·2	0·57
		20	90	70	25·7		36	1·64
		25	72	52	34·6		48·4	8·7
1·0	10	20	180	170	21·17	1·3	27·5	0·425
		25	144	134	26·85		34·9	0·79
		30	120	110	32·7		42·5	1·44
		35	102·8	92·8	38·8		50·5	2·9
	20	20	180	160	22·5	1·3	29·25	0·5
		25	144	124	29		37·7	0·98
		30	120	100	36		45·5	1·85
		35	102·8	82·8	43·5		56·6	5·7
2·0	10	20	360	350	20·57	1·2	24·7	0·237
		25	288	278	25·9		31·1	0·4
		30	240	230	31·3		37·6	0·65
		35	206	196	36·7		44	1·0
	20	20	360	340	21·08	1·2	25·3	0·25
		25	288	268	26·85		32·2	0·44
		30	240	220	32·7		39·3	0·73
		35	206	186	38·7		46·4	1·2
	30	20	360	330	21·8	1·2	26·2	0·27
		25	288	258	27·9		33·5	0·48
		30	240	210	34·3		41·2	0·83
		35	206	176	40·9		49·1	1·43

consider that the run of $\frac{1}{2}$ mile between stops is to be made at a schedule speed of 20 ml.p.h., with a stop of 20 seconds, other conditions being as above. Then we have

$$\text{Schedule time} = 0{\cdot}5 \times 3600/20 = 90 \text{ sec.}$$
$$\text{Running time} = 90 - 20 = 70 \text{ sec.}$$
$$\text{Average speed} = 0{\cdot}5 \times 3600/70 = 25{\cdot}7 \text{ ml.p.h.}$$

TABLE IV

Schedule Speeds corresponding to Various Services.

Distance between Stops.	Acceleration.	Braking Retardation.	Maximum Speed.	Ratio :— Maximum Speed / Average Speed	Average Speed.	Running Time.	Duration of Stop.	Schedule Time.	Schedule Speed.
miles.	ml.p. h.p.s.	ml.p. h.p.s.	ml.p.h.		ml p.h.	seconds.	seconds.	seconds.	ml.p.h.
0·5	1·0	2·0	31·2	1·4	22·3	80·7	10	90·7	19·6
							20	100·7	17·8
	1·25		33·3		23·8	75·6	10	85·6	21
							20	95·6	18·8
	1·5		35·1		25·1	71·7	10	81·7	22
							20	91·7	19·6
	1·75		36·7		26·2	68·7	10	78·7	22·9
							20	88·7	20·3
	2 0		38		27·2	66·1	10	76·1	23·6
							20	86·1	20·9
1·0	0·75	2·0	34·3	1·3	26·4	136·5	10	146·5	24·6
							20	156·5	23
	1·0		38		29·25	123	10	133	27·1
							20	143	25·2
	1·25		40·8		31·4	114·6	10	124·6	28·9
							20	134·6	26·7
	1·5		43		33·1	108·8	10	118·8	30·8
							20	128·8	28
	2·0		46·5		35·8	100·5	10	110·5	32·6
							20	120·5	29·9
2·0	0·5	2·0	34	1·2	28·4	254	20	274	26·3
							30	284	25·4
	0·75		39·6		33	218	20	238	30·3
							30	248	29
	1·0		43·8		36·5	197	20	217	33·2
							30	227	31·7
	1·25		47·1		39·3	183·5	20	203·5	35·4
							30	213·5	33·7

Note.—The maximum speed is obtained from equation (2), thus :—

$$\left(\frac{1}{\alpha}+\frac{1}{\beta}\right)=\frac{7200D}{V_m^2}\left(\frac{V_m}{V_a}-1\right),$$

or

$$V_m=\sqrt{\frac{\alpha\beta}{\alpha+\beta}\left[7200D\left(\frac{V_m}{V_a}-1\right)\right]},$$

the ratio $\frac{V_m}{V_a}$ being known.

The maximum speed is 40 per cent greater than the average speed (i.e. maximum speed = $1{\cdot}4 \times 25{\cdot}7 = 36$ ml.p.h.). Inserting this value in equation (2) we obtain

$$\frac{1}{a} = \frac{7200 \times 0{\cdot}5}{(36)^2}(1{\cdot}4 - 1) - \tfrac{1}{2} = 0{\cdot}61$$

whence $a = 1{\cdot}64$ ml.p.h.p.s.

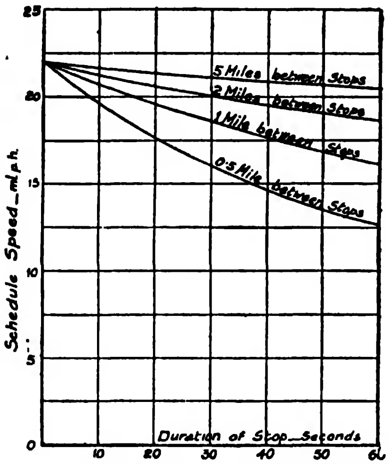


FIG. 5.—Influence of Duration of Stop and Length of Run on Schedule Speed.

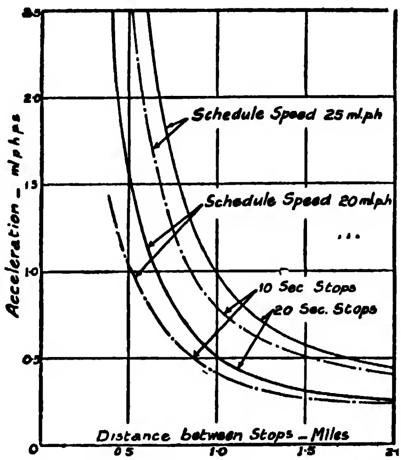


FIG. 6.—Minimum Acceleration to maintain given Schedule Speeds with various Distances between Stops.

Table IV gives the schedule speeds, corresponding to various values of acceleration, for various conditions, the rate of braking and ratio of maximum to average speed being the same as in Table III.

FIG. 7.—Schedule Speeds corresponding to runs of 0·5, 1·0, and 2·0 miles, with various Values of Acceleration.

The results of Tables II, III, and IV are plotted in Figs. 5, 6, and 7.

A study of these tables and curves shows the necessity of a high

acceleration, if a high schedule speed is desired, in urban and suburban service. It is evident that no steam locomotive could run a service at a schedule speed of 20 ml.p.h. with a stop every ½ mile, even when the duration of the stop is only 10 seconds, but it is quite within the range of electric traction to run this service with a stop of 20 seconds' duration.

When we consider longer distances (e.g. above 1 mile) between stops, the importance of a high acceleration is not so marked, and a steam locomotive would be quite capable of running a service at a schedule speed of over 25 ml.p.h. with a stop of 30 seconds' duration at stations 2 miles apart.

CHAPTER III

THE MECHANICS OF TRAIN MOVEMENT

II. Preliminary Investigation of Energy Consumption

We have shown how the speed of a train can be represented during any interval of its motion, and it is now necessary to consider the manner in which the energy required can be estimated.

When electricity is applied to the operation of tramway and railway systems from a central power station, it is necessary to predetermine the amount of power required by the cars and trains, in order that the power-station equipment, substations, feeders, etc., may be designed for economical working. The degree of accuracy to which this predetermination is possible will depend on the exactness of the available knowledge relating to the conditions of operation, such as schedule speed, distance between stops, frequency of service, weight of cars, etc. Thus, on railways, the schedule speeds are fixed by time-tables, and the operating conditions are known, but with street tramways the schedule speeds and the operating conditions are very variable. For the case of a tramway system an exact estimation of the energy required is not essential, as, apart from the variable conditions met with in street traffic, the maximum power taken by a tramcar does not usually exceed 75 kW. On the other hand, the maximum power required by a train may exceed 2000 kW., and therefore an accurate estimation of the energy required in this case is essential.

The total energy supplied to an electric train for propulsion may be expended in five ways, viz. (1) in accelerating the train in a horizontal direction; (2) in accelerating the revolving parts; (3) in doing work against gravity, if the train is ascending a gradient; (4) in doing work against the resistances to motion; and (5) in supplying the losses in the motors and electrical equipment.

For short-distance runs on level track at high schedule speeds, the energy required for acceleration forms a large percentage of the total energy supplied for propulsion. On the other hand, with long-distance runs on level track at high speeds the energy expended against the resistances to motion may be considerably greater than that required for acceleration.

The energy expended in accelerating the train is converted into kinetic energy and therefore represents stored energy which is recoverable for propulsion purposes. A portion of this stored energy is utilized during coasting and the remainder is dissipated as heat in the brake shoes.

Determination of energy required for propulsion. The determination of the energy required for acceleration, and also for the other items (except the losses in the motors) enumerated above, involves only the application of elementary dynamics. The work done during a period of uniform acceleration from rest, the work done against gravity, and the energy expended against the resistances to motion can all be determined

directly from simple expressions when no variable factors are involved. But with variable acceleration and resistances to motion the work done must be calculated by a point-to-point method which involves the separate consideration of the quantities (i.e. force, speed, time) concerned. We shall, therefore, show how to calculate the force necessary for acceleration.

Tractive force for acceleration. The fundamental dynamical equation concerned with the acceleration of a body in a horizontal direction is

Acceleration = accelerating force/mass of body

When British units are employed the acceleration is expressed in feet per second per second, and, if the accelerating force is expressed in pounds, the mass of the body must be expressed in engineer's mass units, i.e. (weight in lb./gravitational acceleration in ft. per sec. per sec.) or w/g where w is the weight in lb. and g is the gravitational acceleration in ft. per sec. per sec. In this country the value of g is taken at 32·2.

If, however, the acceleration is to be expressed in miles per hour per second (a) and the weight in tons (W), then for the accelerating force (F) to be in lb., we must have

$$a(5280/3600) = F/(2240W/32{\cdot}2)$$

whence

$$F = Wa[2240 \times 5280/(3600 \times 32{\cdot}2)]$$
$$= 102Wa.$$

Therefore to obtain an acceleration of 1 mile per hour per second (or 1·467 feet per second per second) an accelerating force of 102 pounds is necessary for each ton accelerated.

This relationship, however, only holds good provided that the body being accelerated possesses no rotating parts. But with electric trains the wheels, axles, motor armatures, and gearing have to be accelerated in an angular direction at the same time as the whole train is accelerated in a linear direction. The force required for the angular acceleration of these parts is determined from the fundamental relationship

Angular acceleration = accelerating torque/moment of inertia.

In this equation the angular acceleration is expressed in radians per sec. per sec. when the accelerating torque is expressed in lb.-ft. and the moment of inertia is expressed in engineer's mass units and (feet)². Thus

$$a_a = \mathfrak{T}/(k^2\, w/g)$$

where a_a denotes the angular acceleration in radians per sec. per sec., $\mathfrak{T}$ the accelerating torque in lb.-ft., k the radius of gyration in ft., w the weight of the rotating body in lb., g the value of gravitation acceleration in ft. per sec. per sec.

[NOTE.—Moment of inertia = mass × (radius of gyration)² = $(w/g)k^2$.]

Hence, if we have a wheel, of weight W_1 tons and radius of tread r_1 ft., rotating about its axis, and a force F_1 lb., in addition to that necessary to balance the rotational frictional resistances, is applied to the periphery, then the angular acceleration of the wheel will be given by

$$a_a = F_1 r_1/(k_1^2 \times 2240W_1/32{\cdot}2)$$

But, if the wheel forms part of a train which is being accelerated linearly at a m.p.h.p.s., the angular acceleration in radians per sec.

per sec. = (linear acceleration of tread of wheel in ft. per sec. per sec./radius of tread in ft.), i.e.

$$a_a = (5280/3600)\, a/r_1$$

whence
$$F_1 = (W_1 a k_1^2/r_1^2) \times [2240 \times 5280/(32{\cdot}2 \times 3600)]$$
$$= 102 W_1 a (k_1/r_1)^2$$

In the case of an armature driven through gearing, of ratio γ, from the axle of the wheel, the angular acceleration of the armature will be γ times the angular acceleration of the wheel. Hence if W_2 is the weight, in tons, of the armature and k_2 its radius of gyration, in feet, the torque at the *armature shaft* necessary for an angular acceleration γa_a is given by

$$\mathfrak{T}_1 = \gamma a_a\, k_2^2 W_2 \times 2240/32{\cdot}2$$

But the torque at the axle of the wheel will be $\gamma \mathfrak{T}_1$, since the angular velocity of the wheel is $(1/\gamma)$ of that of the armature. Therefore, the force (F_2 lb.) at the tread of the wheel* necessary for the angular acceleration of the armature is

$$F_2 = \gamma \mathfrak{T}_1/r_1 = W_2 a_a \gamma^2 (k_2^2/r_1) \times 2240/32{\cdot}2$$
$$= W_2 a \gamma^2 (k_2^2/r_1^2) \times [2240 \times 5280/(32{\cdot}2 \times 3600)]$$
$$= 102 W_2 a \gamma^2 k_2^2/r_1^2$$
$$= 102 W_2 a \gamma^2 (k_2/r_2)^2\, (r_2/r_1)^2$$

Similarly the force (F_3 lb.) at the tread of the wheel necessary for the angular acceleration of the gear wheel (of weight W_3 tons and radius of gyration k_3 ft.) is

$$F_3 = 102 W_3 a (k_3/r_1)^2$$

and that (F_4) necessary for the angular acceleration of the axle (of weight W_4 tons and radius of gyration k_4 ft.) carrying the wheels is

$$F_4 = 102 W_4 a (k_4/r_1)^2$$

In practice the last item (F_4) will be extremely small in comparison with the other items ($F + F_1 + F_2$) and may, therefore, be neglected.

Hence the force (F_a lb.) acting at the treads of the driving wheels (and called, therefore, the **tractive force**) necessary for the acceleration, on level track, of an electric train made up of motor and trailer coaches will be

$$F_a = F + 2n_1 F_1 + n_2 F_2 + n_2 F_3$$

where n_1 is the number of axles, n_2 the number of motors, F the force for the linear acceleration of the dead weight of the train, $2n_1 F_1$ the force for the angular acceleration of the wheels (which are all assumed to be identical), and $n_2 F_2$, $n_3 F_3$ the forces for the angular acceleration of the armatures and gear wheels, respectively. Whence

$$F_a = 102 W a + 102 W_1 a \,.\, 2n_1 \left(\frac{k_1}{r_1}\right)^2 + 102 W_2 a n_2 \gamma^2 \left(\frac{k_2}{r_2}\right)^2 \left(\frac{r_2}{r_1}\right)^2 + 102 W_3 a n_2 \left(\frac{k_3}{r_1}\right)^2$$

$$= 102a \left\{ W + 2n_1 W_1 \left(\frac{k_1}{r_1}\right)^2 + n_2 W_2 \gamma^2 \left(\frac{k_2}{r_2}\right)^2 \left(\frac{r_2}{r_1}\right)^2 + n_2 W_3 \left(\frac{k_3}{r_1}\right)^2 \right\}$$

$$= 102 a W_e \qquad \qquad (7)$$

* It is necessary to consider this force acting at the tread of the wheel, as the characteristics of the motor are calculated for the output at this point.

where W_e is called the "**effective**" or "**accelerating**" **weight** of the train.

The amount by which W_e exceeds the dead weight of the train varies from 8 per cent to 15 per cent of the latter, the actual value depending on the number of wheels and motors, type of motor, etc.

In order to calculate the effective weight of a train, it is necessary to know the radius of gyration of each rotating part. The radius of gyration of a cylinder is 0·707 × external radius; an average value for a steel-tyred railway wheel is 0·77 × radius of tread; while, for the armature of a direct-current or alternating-current commutator motor, the value of 0·7 × external radius of armature core is approximately correct. The radius of gyration of a gear wheel will depend on the design of the wheel, but, for the class of gear wheels used on motor-coach trains, the value of 0·8 × radius of pitch circle will be sufficiently accurate.

Hence, inserting these values in the above equation, we have

$$W_e = W + 2n_1W_1(0\cdot77)^2 + n_2W_2\gamma^2(0\cdot7)^2\left(\frac{r_2}{r_1}\right)^2 + n_2W_3(0\cdot8)^2\left(\frac{r_3}{r_1}\right)^2$$

$$= W + 1\cdot2n_1W_1 + 0\cdot49n_2W_2\gamma^2 \qquad + 0\cdot64n_2W_3\left(\frac{r_3}{r_1}\right)^2 \quad . \quad (8)$$

Example. Calculation of the effective weight of a typical motor-coach train-unit for suburban service.—The train-unit is made up of three 4-wheel bogie coaches and has a weight of 94 tons without passengers. It is equipped with four direct-current motors and each motor is geared to a driving axle through single-reduction gearing having a gear ratio of 2·81. All wheels are $42\frac{1}{2}$ in. in diameter and each wheel weighs 1000 lb. Each motor armature weighs 2350 lb. and the diameter of the armature core is 21 in. Each gear wheel weighs 565 lb. and has a pitch circle diameter of 30 in.

Hence, Number of axles (n_1) = 12

Number of motors (n_2) = 4

Substituting in equation (8), we have

$$W_e = 94 + [1\cdot2 \times 12 \times 1000/2240] + [0\cdot49 \times 4 \times (2350/2240) \times 2\cdot81^2 \times (21/42\cdot5)^2] + [0\cdot64 \times 4 \times (565/2240) \times (30/42\cdot5)^2]$$

$$= 94 + 6\cdot43 + 3\cdot96 + 0\cdot323$$

$$= 104\cdot7 \text{ tons (approximately)},$$

which is 11·5 per cent greater than the dead weight of the train. It will be observed that the effective weight of the gear wheels (0·323 tons) is very small in comparison with the effective weight of the train.

Tractive force for gravitational effect and resistance to motion. When a train is on a gradient the effect of gravity produces a force which tends to cause motion down the gradient. This force is calculated by resolving the vertical gravitational force due to the weight of the train in a direction parallel to the gradient. Thus, if W is the weight of the train, in tons, and θ is the inclination of the gradient to the horizontal, the force (F_g lb.), due to gravity, acting down the gradient is

$$F_g = 2240W \sin \theta.$$

But in railway work gradients are expressed either in terms of distance (along the track) corresponding to a rise of 1 ft. or in terms of the rise

per 100 ft. of track. The former is standard in British railway practice while the latter is customary in American railway practice and gives the "percentage gradient."

Hence, since $\sin\theta =$ (rise or elevation/distance along track), the percentage gradient (G) is equal to $100 \sin\theta$. Whence

$$F_g = 2240W(G/100) = 22{\cdot}4WG$$

It should be observed that for motion of a train up a gradient this force must be balanced by a corresponding increase in the tractive force if the acceleration is to be maintained at the same value as on level track. Conversely, if the train is descending a gradient, the force, F_g, forms part of the accelerating force.

The determination of the tractive force (F_r) necessary to balance the resistances to motion (which are called collectively "train resistance" or "tractive resistance") involves a knowledge of these resistances.

As train resistance is made up of several variable components, none of which can be calculated from first principles, our present knowledge has had to be obtained experimentally. Train resistance in detail is considered later, but for present purposes the specific train resistance (i.e. the resistance per ton of train weight) may be estimated from the following empirical formulae which are based upon experimental results.

For locomotive-hauled trains*

$$r = 2{\cdot}5 + V^{5/3}/(50{\cdot}8 + 0{\cdot}0278nL)$$

and for motor-coach trains†

$$r = 4{\cdot}1 + 0{\cdot}055V + \frac{AV^2}{W}(0{\cdot}0028k + 0{\cdot}0000122nL)$$

where r = specific train resistance in lb. per ton of train weight,
W = weight of train in tons,
V = speed in miles per hour,
n = number of coaches,
A = cross-sectional area (in sq. ft.) at right angles to motion,
L = length of each coach in feet, and
k = a coefficient to include the effect due to the shape of the ends of the coaches.

These formulae refer to train resistance at constant speed. When the speed is changing rapidly, the train resistance is greater than that at constant speed, and therefore during the initial period of acceleration we cannot apply these formulae for the train resistance. Moreover, a relatively large variation in the train resistance, during this period, will have little effect on the dynamical performance of the train, since, in urban service, practically 95 per cent of the total energy output from the driving axles will be expended in acceleration. We are, therefore, justified in assuming an average value for the train resistance during the initial accelerating period, and, in practice, this is usually taken at from 7 to 10 lb. per ton weight of train. During speed-curve running

* The formula does not include the resistance of the locomotive. See paper on "Train Resistance" by Sir John Aspinall, *Minutes of Proceedings of the Institution of Civil Engineers*, vol. 147, p. 155.

† See Chapter XVIII.

(when the acceleration is gradually decreasing), and free running (i.e. constant speed), the train resistance should be obtained from the formulae.

Tractive effort for propulsion of train. The tractive force (F_t) required to propel a train on level track at a constant acceleration is, therefore,

$$F_t = F_a + F_r = 102W_e a + Wr$$

where W, W_e, are the dead and effective weights (in tons), respectively, of the train, a the acceleration in ml.p.h.p.s., and r the specific train resistance.

If the train has to ascend a gradient, then

$$F_t = F_a + F_r + F_g = 102W_e a + Wr + 22{\cdot}4WG$$

while, if the train has to descend a gradient, we have

$$F_t = F_a + F_r - F_g = 102W_e a + Wr - 22{\cdot}4WG$$

Examples. (1) A 200-ton train is to be accelerated on level track at 1·2 ml.p.h.p.s. What tractive effort must be supplied ?

Assuming the effective weight as 220 tons and the train resistance as 10 lb. per ton of train weight, we have

$$F_t = 102 \times 220 \times 1{\cdot}2 + 200 \times 10 = 28{,}920 \text{ lb.}$$

(2) If the tractive effort in the preceding example is maintained constant, while the train ascends a gradient of 1 in 250, what will be the resulting acceleration ?

The percentage gradient (G) is $(1/250) \times 100 = 0{\cdot}4$.

The acceleration is determined from the equation

$$\begin{aligned} a &= (F_t - Wr - 22{\cdot}4WG)/102W_e \\ &= [28{,}920 - 200(10 + 22{\cdot}4 \times 0{\cdot}4)]/102 \times 220 \\ &= 1{\cdot}12 \text{ ml.p.h.p.s.} \end{aligned}$$

Power output from driving axles. The power output from the driving axles at any instant is equal to the product of the tractive effort and speed. If the power (P) is to be expressed in kilowatts, when the tractive effort (F_t) and speed (V) are given in lb. and miles per hour respectively, then

$$\begin{aligned} P &= F_t V \times 5280 \times 746/(60 \times 33{,}000 \times 1000) \\ &= 0{\cdot}002F_t V \qquad (9) \end{aligned}$$

Energy output from driving axles. The energy output during a given period is obtained by determining the area of the power-time (output) curve for that period, or, alternatively, by calculating the mean value of the power output and multiplying this by the time. If the power is expressed in kilowatts and the time is expressed in seconds—as is customary in calculations of speed-time curves—the energy will be given in kilowatt-seconds.

For example, for a run, on level track, made according to the trapezoidal speed-time curve [Fig. 4 (*b*)] the energy output for the accelerating period is

$$J_1 = \tfrac{1}{2}t_1 \times 0{\cdot}002F_t V_m$$

and the energy output for the free running period is

$$J_2 = t_2 \times 0{\cdot}002F_t' V_m$$

where F_t, F_t' denote the tractive efforts during acceleration and free running, respectively, and t_1, t_2 denote the duration of the accelerating and free-running periods, respectively.

Instead of expressing the energy in kilowatt-seconds, it is more convenient for purposes of comparison to introduce the train weight and length of run, and to express the energy in watt-hours per ton-mile, i.e. [energy output in watt-hours/(weight of train in tons × distance of run in miles)].

This quantity is called the **specific energy output** and forms a basis of comparison between the dynamical performances of trains operating to different schedules.

The energy output for a given run represents the energy necessary for dynamical purposes, and is entirely independent of the system of propulsion, except in so far as the latter affects W and W_e. The energy input to the motors will depend on the efficiency of the electrical equipment and the method of speed control.

The energy input to the motors is called the "**energy consumption**" of the train, since it is the energy used for propulsive purposes. The total energy taken from the conductor rails or overhead line will be greater than this by the amount required for lighting, heating, control, and brake apparatus.

The energy consumption can be expressed in "kilowatt-hours per train mile," that is,

$$\frac{\text{energy consumption of train in kilowatt-hours}}{\text{length of run in miles}}$$

or in "watt-hours per ton mile," that is,

$$\frac{\text{energy consumption of train in watt-hours}}{\text{length of run in miles} \times \text{weight of train in tons}}$$

the latter being known as the **specific energy consumption.**

Specific energy output for runs made to simplified speed-time curves. When comparisons are to be made between services operated to simplified speed-time curves [e.g. the trapezium, Fig. 4 (a), or the quadrilateral, Fig. 4 (c)] the specific energy outputs for acceleration and train resistance may be determined from very simple expressions. Thus, the energy expended in accelerating a train from rest to a speed V_m ml.p.h. is given, in kW. sec., by

$$\tfrac{1}{2}(0{\cdot}002V_m \times 102W_e a)t_1$$

Replacing t_1 by V_m/a, converting into watt hours, and dividing by the train weight (W) and distance (D miles), we have

Specific energy expended in acceleration

$$= \tfrac{1}{2}(0{\cdot}002V_m^2 \times 102W_e) \times 1000/(3600WD)$$

$$= \frac{0{\cdot}0283V_m^2}{D} \cdot \frac{W_e}{W} \qquad (10)$$

Similarly, if the train resistance is constant at r lb. per ton over a distance D' miles, the work done against train resistance is $5280D'Wr$ ft.-lb. Converting this into watt-hours per ton mile for a run of D miles, we have

Specific energy expended against train resistance

$$= 5280D'Wr \times 746/(550 \times 3600 \times WD)$$

$$= 1{\cdot}99rD'/D = 2rD'/D \text{ (approximately)} \qquad (11)$$

Whence the energy expended for the run is

$$J = (0{\cdot}0283 V_m^2/D) W_e/W + 2rD'/D \text{ watt-hours per ton-mile,}$$

or, if s is the number of stops per mile ($s = 1/D$), we have

$$J = 0{\cdot}0283 V_m^2 s(W_e/W) + 2r(D'/D) \text{ watt-hours per ton-mile.}$$

A principle which is of importance in comparisons of energy consumption is that, on the assumption of constant train resistance, the specific energy output of a given train is constant for all runs made to speed-time curves of similar shapes. Thus, consider two trapezoidal speed-time curves of similar shape, the ordinates of one (B) being k times those of the other (A). Then the maximum speed of B is k times that of A, and the distance between stops for B is k^2 times that for A (p. 18). Hence the specific energy expended in acceleration is

$$0{\cdot}0283 V_m^2(W_e/W)/D \text{ for speed-time curve } A,$$

and $$0{\cdot}0283(kV_m)^2(W_e/W)k^2D \text{ for speed-time curve } B,$$

i.e. the two quantities are equal.

A similar equality is obtained for the specific energy expended against train resistance provided that the same value of constant train resistance is assumed in each case.

This principle is of considerable use when estimations of energy consumption are required for operating a train service along a given route at various schedule speeds. It may be extended to actual speed-time curves by assuming a definite shape for the speed-curve-running portion of such curves, and with generalized data of motors the energy consumption for any given conditions may be predicted. Such methods are largely employed by electric railway engineers and manufacturers for preliminary purposes.

Factors affecting energy consumption. The specific energy consumption of trains operating at a given schedule speed is influenced by (1) the distance between stops, (2) the acceleration, (3) the retardation, (4) the maximum speed, (5) the type of train and equipment, (6) the configuration of the track.

Generally, for a given run at a given schedule speed, the specific energy consumption will be lower the higher the acceleration and retardation, since by these means a longer coasting period can be obtained. However, due consideration must be given to the weight of the equipment and the effect of this on the energy consumption of the train. For runs of short distances, a low specific energy consumption will generally indicate a low total energy consumption, but for longer distances it does not follow that a similar relation holds, since, in the latter case, the work done against train resistance is a considerable percentage of the total energy output from the axles. Table V shows that, in the case of long-distance runs, the effect of increased acceleration in reducing the specific energy consumption is altogether counteracted by the increased weight of the train leading to a greater total energy consumption.

Table V has been calculated for motor-coach trains weighing 200 and 225 tons operating at various schedules. The 200-ton train is considered to operate with an acceleration of 0·5 ml.p.h.p.s., while for the 225-ton train an acceleration of 1·0 ml.p.h.p.s. has been assumed. The braking

TABLE V

Approximate Energy Consumption of Trains operating on Various Services.

Braking Retardation 1·5 ml.p.h.p.s.

Distance between Stops.	Average Speed.	Running Time.	Accelera-tion.	Maximum Speed.	Distance Travelled.		Specific Train Resistance.*		Weight of Train.	Energy Expended.		Specific Energy Consump-tion.	Energy Consump-tion of Train.	Energy Dissipated in Brakes as Percentage of Total Energy Utilised.
					During Accelera-tion.	During Free-running.	For Ac-celerating Period.	For Free-running Period.		In Accelera-tion.	Against Train Resistance.			
miles.	ml.p.h.	seconds.	ml.p.h.p.s.	ml.p.h.	ml.	ml.	lb. per ton.	lb. per ton.	tons.	wh. per ton mile.	wh per ton mile.	wh. per ton mile.	kwh. per train mile.	
0·75	20	135	1·0	23·4	0·076	0·62	8	8	225	22·7	15	37·7	8·48	60
			0·5	27·5	0·21	0·47	8·3	8·9	200	30·8	16·1	46·9	9·38	65·6
5	35	486	1·0	40	0·22	4·66	10	12·5	225	9·9	24·2	34·1	7·68	29
			0·5	42	0·48	4·39	10·5	13	200	10·8	24·8	35·6	7·12	30·3
30	50	2160	1·0	51	0·45	29·4	13	16·4	225	2·7	32·55	35·25	7·94	7·65
			0·5	51·7	0·74	29·05	13·2	16·7	200	2·72	34	36·7	7·34	7·4

* Assumed.

retardation is 1·5 ml.p.h.p.s. in each case. The effective weight for the 200-ton train has been assumed at 216 tons and at 247 tons for the 225-ton train. The energy output given in the table has been calculated (see below) on the basis of a simplified speed-time curve, consisting of periods of constant acceleration, constant speed, and constant retardation. The large percentage of energy wasted in the brakes for the short-distance runs should be noted.

The method of calculating the quantities in Table V is best illustrated by considering the first run of $\frac{3}{4}$ mile between stops. The average speed is 20 ml.p.h., and consequently the running time is

$$(0{\cdot}75 \times 3600/20 =)135 \text{ sec.}$$

The acceleration is 1·0 ml.p.h.p.s., and the retardation is 1·5 ml.p.h.p.s.

Inserting these values in equation (1) we obtain the maximum speed as 23·4 ml.p.h.

The time of acceleration is (23·4/1·0 =) 23·4 sec., the time of braking is (23·4/1·5 =) 15·6 sec., and the time of free running is 96 sec. The distance traversed during acceleration is ($\frac{1}{2} \times 23{\cdot}4^2/3600 =$) 0·076 ml., and that during free running is ($23{\cdot}4 \times 96/3600 =$) 0·624 ml.

Assuming the specific train resistance during acceleration and free running at 8 lb. per ton, we have: Energy used against train resistance

$$= 2 \times 8 \times (0{\cdot}624 + 0{\cdot}076)/0{\cdot}75 = 15 \text{ watt-hours per ton mile.}$$

The energy used in acceleration

$$= 0{\cdot}0283 \times 23{\cdot}4^2 \times 247/(0{\cdot}75 \times 225) = 22{\cdot}7 \text{ watt-hours per ton mile.}$$

The specific energy consumption (on the assumption of no losses in the train equipment) is $15 + 22{\cdot}7 = 37{\cdot}7$ watt-hours per ton mile, and the total energy consumption is $225 \times 37{\cdot}7/1000 = 8{\cdot}48$ kW. hours per train mile.

Examples. (1) A train service between two stations 1 mile apart, and between which there is a uniform gradient of 1 in 80, is scheduled at an average speed (excluding stops) of 25 ml.p.h. in one direction, viz. up the gradient, and 27·5 ml.p.h. in the opposite direction. The dead weight of the train is 210 tons: the mean tractive effort exerted by the motors during acceleration is 30,000 lb., and the mean braking effort due to the brakes is 47,000 lb. The train resistance may be assumed constant at 12 lb. per ton of train weight.

Calculate the specific energy output and the maximum power developed by the motors for runs, in both directions, made to trapezoidal speed-time curves.

The effective weight of the train may be assumed to be 10 per cent greater than the dead weight.

From the given data we obtain

$W_e = 1{\cdot}1 \times 210 = 231$ tons.

G = percentage gradient $= 100/80 = 1{\cdot}25$.

F_g = force due to gradient $= 22{\cdot}4WG$

$= 22{\cdot}4 \times 210 \times 1{\cdot}25 = 5880$ lb.

Hence, Acceleration up gradient $= (30{,}000 - 5880)/(102 \times 231$

$= 1{\cdot}022$ ml.p.h.p.s.

Acceleration down gradient $= (30{,}000 + 5880)/(102 \times 231)$

$= 1{\cdot}522$ ml.p.h.p.s.

Braking retardation up gradient $= (47{,}000 + 5880)/(102 \times 231)$
$= 2{\cdot}245$ ml.p.h.p.s.
Braking retardation down gradient $= (47{,}000 - 5880)/(102 \times 231)$
$= 1{\cdot}745$ ml.p.h.p.s.
Running time, "up" journey $= 1 \times 3600/25 = 144$ sec.
Running time, "down" journey $= 1 \times 3600/27{\cdot}5 = 131$ sec.

The maximum speeds, calculated from equation (3), are 29·3 ml.p.h. for the "up" journey, and 32·4 ml.p.h. for the "down" journey.

Whence, for the "up" journey—

Duration of accelerating period $= 29{\cdot}3/1{\cdot}022 = 28{\cdot}65$ sec.
Duration of braking period $= 29{\cdot}3/2{\cdot}245 = 13{\cdot}05$ sec.
Duration of free-running period $= 144 - 28{\cdot}65 - 13{\cdot}05 = 102{\cdot}3$ sec.
Distance run during acceleration $= \frac{1}{2} \times 29{\cdot}3 \times 28{\cdot}65/3600 = 0{\cdot}1165$ ml.
Distance run during free running $= 29{\cdot}3 \times 102{\cdot}3/3600 = 0{\cdot}832$ ml.
Distance run during braking $= \frac{1}{2} \times 29{\cdot}3 \times 13{\cdot}05/3600 = 0{\cdot}0531$ ml.
Distance run with power $= 0{\cdot}95$ ml.
Specific energy output for acceleration $= 0{\cdot}0283 \times 29{\cdot}3^2 \times 1{\cdot}1$
$= 26{\cdot}75$ watt-hours per ton mile
Specific energy output for resistances and gravity $= 2(12 + 22{\cdot}4 \times 1{\cdot}25)0{\cdot}95/1{\cdot}0$
$= 76$ watt-hours per ton mile
Specific energy output for "up" journey $= 26{\cdot}75 + 76$
$= 102{\cdot}75$ watt-hours per ton mile

The maximum power output (in h.p.) from the motors occurs at the end of the accelerating period and is equal to

$$30{,}000 \times 29{\cdot}3 \times 5280/(60 \times 33{,}000) = 2345 \text{ h.p.}$$

For the "down" journey—

Duration of accelerating period $= 32{\cdot}4/1{\cdot}522 = 21{\cdot}27$ sec.
Duration of braking period $= 32{\cdot}4/1{\cdot}745 = 18{\cdot}56$ sec.
Duration of free-running period $= 131 - 21{\cdot}27 - 18{\cdot}56 = 91{\cdot}17$ sec.
Distance run during acceleration $= \frac{1}{2} \times 32{\cdot}4 \times 21{\cdot}27/3600 = 0{\cdot}0957$ ml.
Distance run during free running $= 32{\cdot}4 \times 91{\cdot}17/3600 = 0{\cdot}82$ ml.
Duration run during braking $= \frac{1}{2} \times 32{\cdot}4 \times 18{\cdot}56/3600 = 0{\cdot}0834$ ml.
Distance run with power $= 0{\cdot}92$ ml.
Specific energy output during acceleration $= 0{\cdot}0283 \times 32{\cdot}4^2 \times 1{\cdot}1$
$= 32{\cdot}7$ watt-hours per ton mile
Specific energy output during free-running*
Specific energy output for "down" journey $= 32{\cdot}7$ watt-hours per ton mile
Maximum power output $= 30{,}000 \times 32{\cdot}4 \times 5280/(60 \times 33{,}000) = 2590$ h.p.

(2) Referring to example (4), p. 17, if the weight of the train is 200 tons, the effective weight 220 tons, and the train resistance during the accelerating period is 10 lb. per ton, calculate (1) the specific energy output for the run, (2) the energy dissipated in the brakes, (3) the energy utilized during coasting, (4) the mean train resistance during coasting.

From p. 17, we have

Speed (V_1) at end of accelerating period $= 38$ ml.p.h.
Speed (V_2) at end of coasting period $= 26{\cdot}88$ ml.p.h.
Distance run during accelerating period $= 0{\cdot}148$ ml.

Hence the specific energy expended against train resistance during the accelerating period is

$$2 \times 10 \times (0{\cdot}148/1{\cdot}2) = 2{\cdot}47 \text{ watt-hours per ton-mile,}$$

and the specific energy expended in acceleration is

$$0{\cdot}0283 \times 38^2 \times (220/200)/1{\cdot}2 = 37{\cdot}4 \text{ watt-hours per ton-mile.}$$

* As the resultant train resistance is negative ($= 12 - 22{\cdot}4 \times 1{\cdot}25 = -16$) the brakes must be applied during the free-running period to maintain the speed constant.

Whence—

(1) Specific energy output for the run

$$= 37{\cdot}4 + 2{\cdot}47 \qquad = 39{\cdot}87 \text{ watt-hours per ton-mile.}$$

(2) The energy dissipated in the brakes is equal to the energy stored in the train at the end of the coasting period (i.e. at the speed V_2) and is equal to

$$0{\cdot}0283 \times 26{\cdot}88^2 \times (220/200)/1{\cdot}2 = 18{\cdot}72 \text{ watt-hours per ton-mile.}$$

(3) The energy utilized during coasting is, therefore, the difference between items (1) and (2), i.e.

$$37{\cdot}4 - 18{\cdot}72 \quad = 18{\cdot}68 \text{ watt-hours per ton-mile.}$$

(4) The mean train resistance during coasting may be calculated either from the energy utilized during the coasting period or from the given value of the coasting retardation. In the latter case, if r_c is the mean train resistance (in lb. per ton of train weight) during coasting, β_c the coasting retardation in ml.p.h.p.s., then

$$r_c = 102\beta_c(W_e/W),$$

and, since $\beta_c = 0{\cdot}1$, therefore

$$r_c = 102 \times 0{\cdot}1 \times (220/200) = 11{\cdot}22 \text{ lb. per ton.}$$

If we wish to calculate this quantity by the alternative method—utilizing equation (11)—we require a knowledge of the distance run during coasting. From p. 17, this distance is given as 1·002 ml. Hence, substituting in equation (11), we have

$$1{\cdot}99r_c \times (1{\cdot}002/1{\cdot}2) = 18{\cdot}68$$

or

$$r_c = 11{\cdot}22 \text{ lb. per ton.}$$

(3) Referring to example (1) above, calculate the specific energy output when the "down" run is made to a quadrilateral speed-time curve, the average speed and other data being the same as in example (1). The train resistance during coasting may be assumed to be constant at 15 lb. per ton of train weight.

From the data on p. 33 we have—

Acceleration	$= 1{\cdot}522$ ml.p.h.p.s.
Braking retardation	$= 1{\cdot}745$ ml.p.h.p.s.
Coasting retardation	$= (28-15)/102 \times 1{\cdot}1 = -0{\cdot}116$ ml.p.h.p.s.

By substituting in equation (5), p. 15, we obtain

$$V_1 = 24{\cdot}9 \text{ ml.p.h.},$$

and by substituting in equation (4), we have

$$V_2 = 39{\cdot}33 \text{ ml.p.h.}$$

Whence,

Duration of accelerating period	$= 24{\cdot}9/1{\cdot}522 = 16{\cdot}35$ sec.
Duration of braking period	$= 39{\cdot}33/1{\cdot}745 = 22{\cdot}55$ sec.
Duration of coasting period	$= 131 - 16{\cdot}35 - 22{\cdot}55 = 92{\cdot}1$ sec.
Distance run during acceleration	$= \frac{1}{2} \times 24{\cdot}9 \times 16{\cdot}35/3600 = 0{\cdot}0565$ ml.
Distance run during coasting	$= \frac{1}{2}(24{\cdot}9 + 39{\cdot}33) \times 92{\cdot}1/3600 = 0{\cdot}822$ ml.
Distance run during braking	$= \frac{1}{2} \times 39{\cdot}33 \times 22{\cdot}55/3600 = 0{\cdot}123$ ml.

Specific energy output for acceleration $= 0{\cdot}0283 \times 24{\cdot}9^2 \times 1{\cdot}1$
$= 19{\cdot}3$ watt-hours per ton mile

Specific energy output for train resistance $= 2 \times 12 \times 0{\cdot}056/1{\cdot}0$
$= 1{\cdot}35$ watt-hours per ton mile

Specific energy output for "down" journey
$= 20{\cdot}65$ watt-hours per ton mile

CHAPTER IV

DIRECT-CURRENT TRACTION MOTORS

General Considerations

With a knowledge of the dynamical requirements involved in the movement of trains and vehicles we can now investigate the dynamical performances of the different types of motors to ascertain their suitability for traction purposes.

Since, with all forms of electric traction, the tractive force at the treads of the driving wheels is always proportional to the torque at the armature shaft of the motor, the relationship between the speed, torque, and current input to the motor are of fundamental importance.

Torque-current characteristics. The relationship between the torque and armature current of any direct-current motor is given by the equation

$$\mathfrak{T} = (p/a)\Phi Iz/852 \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

or

$$\mathfrak{T} = p\Phi \,.\, IN/426 \quad . \quad . \quad . \quad . \quad . \quad . \quad (12a)$$

where $\mathfrak{T}$ is the gross torque (in lb.-ft.), p the number of poles, a the number of circuits in the armature winding, Φ the flux per pole (in megalines), I the current input to the armature, z the number of active armature conductors, N $(= \frac{1}{2}z/a)$ the number of turns per armature circuit.

Hence for a given number of poles the torque is proportional to the product of flux and armature ampere-turns, or for any given motor the torque is proportional to the product of flux and armature current.

Therefore with a motor in which the flux is constant (e.g. a shunt motor supplied at constant voltage) the torque is directly proportional to the *armature* current. But if the voltage at the terminals of the shunt winding decreases, due to voltage drop in the line wires supplying the motor, the proportionality between torque and armature current will, for the higher values of the latter, depart from the straight-line relationship.

With a motor in which the flux varies with the armature current (e.g. a series motor) the variation of torque will always be greater than the corresponding variation of current. Moreover, with such a (series) motor the torque corresponding to a given current will be unaffected by variations in the line voltage.

In Fig. 8 are given calculated torque armature-current curves for shunt and series motors in which the armature windings and magnetic circuits are assumed to be identical and the effects of armature reaction are ignored. These curves are calculated from equation (12), together with data of the armature winding and the magnetization curve.

The effect of voltage variation at the terminals of the shunt winding upon the torque is indicated by the curves IIa, IIb, which correspond to voltages of 80 per cent and 60 per cent of normal, respectively, curve II corresponding to normal voltage.

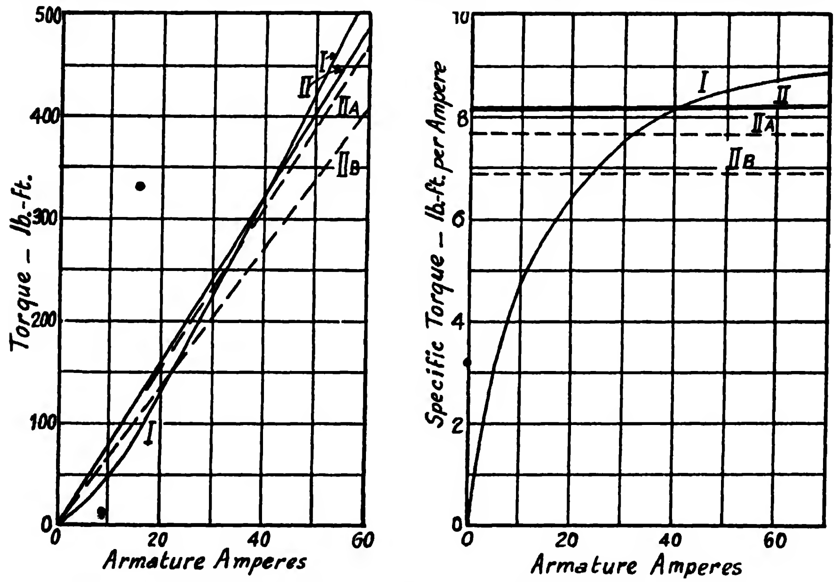
The variation of torque with current is shown better in Fig. 9. in

which the specific torque (i.e. torque per ampere of armature current) is plotted against armature current. Incidentally, these curves show also the variation of flux with armature current, since—from equation(12a)—

$$\mathfrak{T}/I = (pN/426)\Phi \quad . \quad . \quad . \quad . \quad . \quad . \quad (12b)$$

The curves of Figs. 8 and 9 show also the starting performances of shunt and series motors.

From a study of these curves we conclude that when a large torque is required the current input to a series motor will be lower than that to a corresponding shunt motor, even when the latter is operated under the most favourable conditions, viz., constant voltage. In traction systems,



FIGS. 8, 9.—Torque Curves for Direct-Current Series (I) and Shunt (II) Motors.

however, the line voltage is subject to large fluctuations, and the conditions at starting may result in the voltage at the car being appreciably below normal. Hence under these conditions the difference between the armature currents for a given torque will become greater as the line voltage is reduced below normal. Of course, by highly saturating the magnetic circuit of the shunt motor, the effect of voltage variation upon the torque will be smaller, but this procedure would be impracticable with traction motors owing to the restricted space available for the field winding.

Speed-current and speed-torque characteristics. The equation for the speed of a direct-current motor is obtained from the fundamental equation for the E.M.F. generated in the armature, i.e.

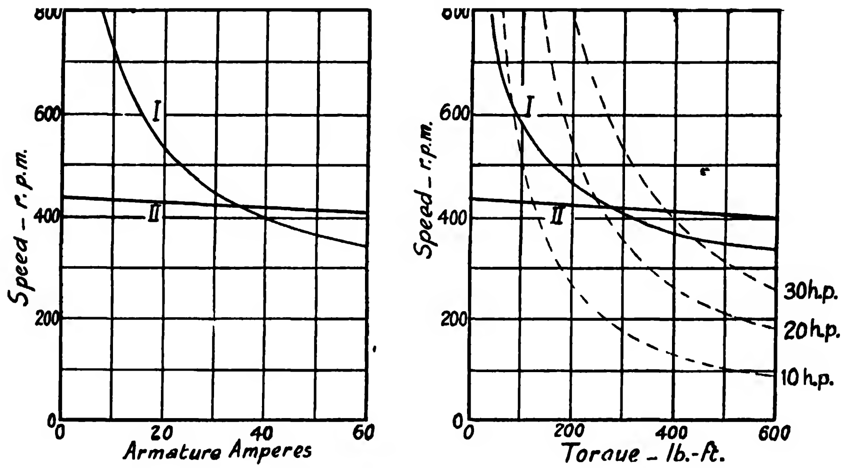
$$V - Ir = \frac{n}{60} \cdot \frac{p}{a} \cdot z\Phi \times 10^{-8}$$

whence

$$n = \frac{6000\,(V - Ir)}{z\Phi\, p/a} = \frac{3000\,(V - Ir)}{pN\Phi} \qquad (13)$$

where n is the speed in revolutions per minute, V the voltage at the terminals of the motor, r the resistance of the main circuit (including the series field winding, if any), and I, p, a, z, N, Φ have the same significance as previously. For a given motor the speed is, therefore, proportional to the ratio $(V - Ir)/\Phi$, i.e. counter-E.M.F./flux.

Hence if the line voltage is constant and the effects of armature reaction are ignored, the speed-current and speed-torque characteristic for a shunt motor can be calculated quite easily from equations (12), (13). But with a series motor a knowledge of the magnetic characteristic or saturation curve is necessary, together with data of the armature and



FIGS. 10 11.—Speed-Current and Speed-Torque Curves for Series (I) and Shunt (II) Motors.

field windings, before these characteristics can be pre-determined. If, however, the torque-current curve is available the speed-current curve can be readily obtained, as, by combining equations (12b) and (13), we have

$$n = \frac{3000\,(V - Ir)}{426\,\mathfrak{T}/I} = 7{\cdot}05\,\frac{(V - Ir)}{\mathfrak{T}/I} \quad . \quad . \quad (13a)$$

With the speed-current and torque-current curves available, the speed-torque characteristic can be determined quite easily.

In Fig. 10 are given the calculated speed-current curves at supply voltages of 100 per cent, 80 per cent, and 60 per cent normal voltage for the shunt and series motors previously considered. From these curves and the torque-current curves of Fig. 8 we obtain the speed-torque curves of Fig. 11, which represent the dynamical performances of the motors.

EXAMPLES. (1) The relationship between the current and torque of a series motor—determined by a static test—is as follows—

Current (amp.) .	10	20	30	40	50	60	70	80
Torque (lb.-ft.) .	33	95	170	258	346	450	565	670

Deduce the speed curve of the motor when supplied at a constant voltage of 500 volts, having given: resistance of main circuit of motor = 0·5 ohm.

The calculation is best effected in tabular form, employing equation (13*a*), i.e. $n = 7{\cdot}05(V - Ir)/(\mathfrak{T}/I)$.

I	10	20	30	40	50	60	70	80
$\mathfrak{T}/I$	3·3	4·75	5·66	6·45	6·92	7·5	8·07	8·37
Ir	5	10	15	20	25	30	35	40
$V-Ir$	495	490	485	480	475	470	465	460
$(V-Ir)/(\mathfrak{T}/I)$	150	103·2	85·7	74·4	68·6	62·7	57·6	55
$n = 7{\cdot}05\,(V-Ir)/(\mathfrak{T}/I)$	1057	728	604	524	483	422	406	388

(2) The magnetization curve of a 4-pole series traction motor—determined by separately exciting the field winding, and connecting a voltmeter across the brushes and driving the armature at a constant speed of 500 r.p.m.—is as follows—

Field amperes	50	100	150	200	250	300	350
Armature volts	240	380	446	488	522	550	576

Determine the speed-torque curve for this motor when operating at a constant voltage of 600, having given that the armature has a two-circuit winding with 97 turns per circuit, the resistance of the armature winding and brushes is 0·06 ohm, and the resistance of the field windings is 0·05 ohm.

The relationship between the flux per pole and exciting current is obtained from the no-load magnetization curve by the application of the fundamental E.M.F. equation: $E = (p/a)\, z\, \Phi\, n \times 10^{-2}$, or $E = 2p\, N\, \Phi\, n \times 10^{-2}$. In the present case $p = 4$, $N = 97$, $n = 500/60 = 8{\cdot}33$, so that

$$\Phi = E \times 10^2/(8 \times 97 \times 8{\cdot}33) = 0{\cdot}01546E$$

Whence—

Field amperes	50	100	150	200	250	300	350
Armature volts	240	380	446	488	522	550	576
Flux per pole (megalines)	3·71	5·88	6·9	7·55	8·07	8·5	8·9

The speed can now be calculated by the application of equation (13), i.e.

$$n \text{ r.p.m.} = 3000(E - IR)/(pN\Phi) = 7{\cdot}74\,(600 - 0{\cdot}11I)/\Phi$$

and the torque can be determined by the application of equation (12*a*), i.e. $\mathfrak{T} = p\Phi IN/426 = 0{\cdot}91\,\Phi\, I$, Φ being expressed in megalines in both cases. The calculations are given in tabular form—

Amperes input (I)	50	100	150	200	250	300	350
Internal E.M.F.($= 600-0{\cdot}11I$)	594·5	589	583·5	578	572 5	567	561·5
Speed—r.p.m. [$= 7{\cdot}74\,(600-0{\cdot}11)/\Phi$]	1240	775	654	592	549	516	488
Torque—lb.-ft. ($= 0{\cdot}91\Phi I$)	169	536	942	1375	1837	2320	2835

Comparison of dynamical performances of shunt and series motors. Comparing the dynamical performances of each type of motor with the dynamical requirements of tramway and suburban railway services, we observe that the characteristics of the series motor are better suited to these conditions than those of the shunt motor. Thus (1) the series motor is capable of exerting a large torque at starting, which, for a given current, is independent of fluctuations of the line voltage; (2) this motor possesses a high free-running speed; (3) the speed automatically decreases when the torque increases, thereby protecting the motor against excessive overloading. This self-protective property is of immense value in practice, and is shown by the torque-output curves of Fig. 12, which have been deduced from the speed-torque curves of Fig. 11.

Speed-output curves are also given in Fig. 12. These curves show that if large outputs at high speeds—such as would be necessary for express passenger service on main-line railways—are required from series

motors having characteristics similar to those in Fig. 11, the output at low speeds will be excessive, and the resulting tractive effort may cause unduly large stresses in the rolling stock. In these cases the low speeds must be obtained either by decreasing the voltage at the terminals of the motors or by increasing the number of turns in the field winding (tapped-field control). Both methods are discussed in detail later.

Electrical operation of series and shunt motors under traction service conditions. We will now compare the electrical operation of series and shunt motors under conditions likely to occur in actual service. Confining our attention to tramway and suburban railway services—which require the use of passenger cars equipped with two or four motors per car—the first item of importance is the manner in which the **division of load between the several motors** is affected by (*a*) differences in the diameters of the driving wheels, such as would be caused in practice by unequal wear of the tyres ; (*b*) differences in the speed curves of the motors, such as would occur with slight inequalities in the air gaps of the motors, or slight inequalities in the magnetic characteristics of the materials employed.

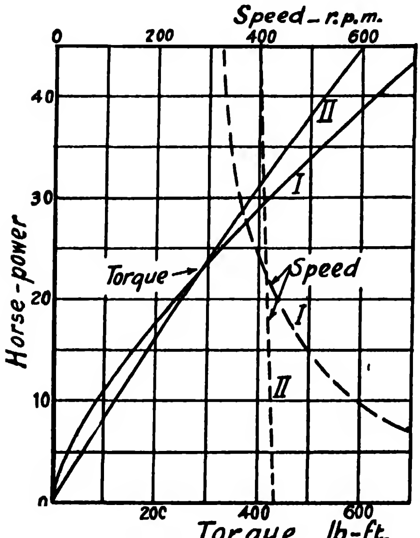


FIG. 12.—Output Characteristics of Series (I) and Shunt (II) Motors.

In general, these conditions have an adverse effect upon the operation of shunt motors but have very little effect upon the operation of series motors, the inequality of the division of load being greater for motors possessing "flat" speed-torque characteristics than for machines having "steep" speed-torque characteristics.

The comparison is best shown quantitatively.

I. **Series motors, parallel operation, unequal wheel diameters.** Consider a car to be equipped with two motors each having a speed curve identical with curve I, Fig. 13. Let one motor (*A*) drive wheels 30 in. in diameter, and let the other motor (*B*) drive wheels 29½ in. in diameter. Then for a given speed of the car the speed of armature *B* will be (30/29·5 =) 1·017 times that of armature *A*. Hence when the motors are connected in parallel the current input to each will be obtained from points on the speed curve corresponding to these speeds. For example, if for a given speed of the car the speed of *A* is 390 r.p.m., the speed of *B* will be (1·017 × 390 =) 397 r.p.m. Whence, from Fig. 13, the current inputs are 41·5 A and 39·5 A respectively. The division of the load between the motors is, therefore, affected only slightly by the inequalities in the wheel diameters.

IA. **Series motors, series operation, unequal wheel diameters.** The

current in each motor is now the same, but the terminal voltages are unequal. In these circumstances the results are best obtained analytically. Thus, if V is the line voltage, V_A, V_B the terminal voltages of the motors A, B respectively, n_A, n_B the speeds of these motors, r the resistance of each, and I the current input, then, from equation (13), we have

$$n_A/n_B = (V_A - Ir)/(V_B - Ir),$$

and $$V_A + V_B = V$$

Solving these equations, we obtain

$$V_A = \frac{V - Ir}{1 + n_B/n_A} + \frac{Ir}{1 + n_A/n_B}$$

$$V_B = \frac{V - Ir}{1 + n_A/n_B} + \frac{Ir}{1 + n_B/n_A}$$

If n_A' is the speed corresponding to a current I and normal voltage V, then

$$n_A = n_A'(V_A - Ir)/(V - Ir)$$

Example. If $n_A/n_B = 1/1{\cdot}017$ as above, $V = 500$, $Ir = 45$, $n_A' = 390$,

$$V_A = \frac{500 - 45}{1 + 1{\cdot}017} + \frac{45}{1 + 1/1{\cdot}017} = 248{\cdot}2 \text{ volts}$$

$$V_B = \frac{500 - 45}{1 + 1/1{\cdot}017} + \frac{45}{1 + 1{\cdot}017} = 251{\cdot}8 \text{ volts}$$

$$n_A = 390(248{\cdot}2 - 45)/(500 - 45) = 171{\cdot}2 \text{ r.p.m.}$$

$$n_B = 1{\cdot}017 n_A = 177{\cdot}2 \text{ r.p.m.}$$

II. **Shunt motors, parallel operation, unequal wheel diameters.** If the car were equipped with two motors having speed curves identical with curve II, Fig. 13, the current inputs corresponding to 390 r.p.m. and 397 r.p.m. are 41·5 A. and 24·2 A., respectively. In this case the motors are loaded very unequally.

IIA. **Shunt motors, series operation, unequal wheel diameters.** When the armatures are connected in series and each motor is normally excited, the load is almost equally divided. Thus, applying the equations obtained for the series-connected series motors, but taking $Ir = 30$ volts instead of 45 volts, we have

$$V_A = \frac{500 - 30}{1 + 1{\cdot}017} + \frac{30}{1 + 1/1{\cdot}017} = 248{\cdot}2 \text{ volts}$$

$$V_B = \frac{500 - 30}{1 + 1/1{\cdot}017} + \frac{30}{1 + 1{\cdot}017} = 251{\cdot}8 \text{ volts}$$

Input to armature $A = 41{\cdot}5 \times 248{\cdot}2 = 10{,}290$ watts

Input to armature $B = 41{\cdot}5 \times 251{\cdot}8 = 10{,}450$ watts

$$n_A = 390\,(248{\cdot}2 - 30)/(500 - 30) = 181 \text{ r.p.m.}$$

$$n_B = 1{\cdot}017 \times 181 = 184{\cdot}2 \text{ r.p.m.}$$

III. **Compound motors, parallel operation, unequal wheel diameters.** With motors having speed curves identical with curve III, Fig. 13, the

current inputs corresponding to armature speeds of 390 r.p.m. and 397 r.p.m. are 41·5 A. and 35·8 A. respectively.

IV. **Parallel operation, equal wheel diameters, dissimilar speed curves.** Assuming a 2½ per cent difference at normal speed (390 r.p.m.), the current inputs to the motors are obtained from the points on the appropriate speed curves which correspond to the actual armature speeds. For example, with series motors having speed curves represented by curves IA, IB, Fig. 13, the currents corresponding to equal armature speeds of 390 r.p.m. are 41·5 A. and 44·5 A. respectively. With shunt motors

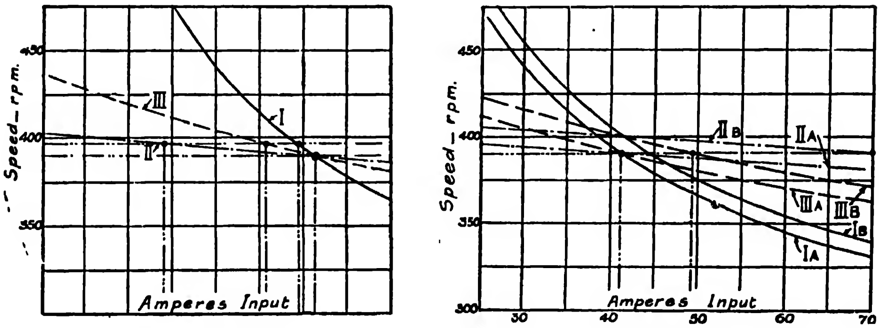


FIG. 13.—Illustrating effects of (*a*) Differences in Diameters of Driving Wheels, (*b*) Differences in Speed Curves, on Current Input to Two Motors, of various Types, connected in Parallel.

under similar conditions (curves IIA, IIB, Fig. 13) the armature currents are 41·5 A. and 72 A. respectively.

Summarizing the results for parallel operation, we have

Type of Motor	Reference to Speed Curves. Fig. (13)		Diameter of Driving Wheels (in.)		Speed of Armatures (r.p.m.)		Current Input (Amperes)	
	Motor A.	Motor B.	Motor A.	Motor B.	Motor A.	Motor B.	Motor A	Motor B.
Series .	IA	IA	30	29·5	390	397	41·5	39·5
Series .	IA	IB	30	29·5	390	397	41·5	42·3
Series .	IA	IB	29·5	30	397	390	39·5	44·5
Shunt .	IIA	IIA	30	29·5	390	397	41·5	24·2
Shunt .	IIA	IIB	30	29·5	390	397	41·5	50
Shunt .	IIA	IIB	29·5	30	397	390	24·2	72
Compound	IIIA	IIIA	30	29·5	390	397	41·5	35·8
Compound	IIIA	IIIB	30	29·5	390	397	41·5	44
Compound	IIIA	IIIB	29·5	30	397	390	35·8	49·5

It is apparent, therefore, that if shunt motors were adopted for electric traction the permissible deviation from the standard speed-curve would have to be considerably smaller than that shown in Fig. 13,

which is equivalent to 2·5 per cent of normal speed (390 r.p.m.). Moreover, all the driving wheels of a car or a train would require frequent gauging, as only slight differences in the diameters would be permissible.

Other important items which require consideration in comparing the electrical performances of series and shunt motors are **pressure rises** and **temporary interruptions in the supply.** The former may occur on low-voltage railways when a heavy current, due to a short circuit on the track, is cleared by the opening of the substation circuit breakers, and temporary interruptions in the supply to the motors occur when cross-overs and section-insulators are crossed with the controller "on." These operating conditions are peculiar to traction service and therefore require special consideration.

Pressure rises. When a motor is subjected to a sudden pressure-rise the initial value of the current-rush is determined by the impedance of the motor circuit, and the duration of this current-rush depends upon the rate at which the counter-E.M.F. of the motor is built up. The current-rush will, therefore, have a lower initial value, and will be of shorter duration, in series motors than in compound or shunt motors.

Temporary interruption of supply. When the supply is briefly interrupted and restored at full voltage, there is a characteristic difference between the operation of series and shunt motors. With a shunt motor the counter-E.M.F. is maintained—at decreasing value—during the interruption, but with a series motor the counter-E.M.F. ceases when the interruption occurs. Upon the restoration of the supply voltage, the shunt machine will have a certain counter-E.M.F., and the initial value of the current-rush will be determined by the resultant E.M.F. and the impedance of the armature circuit. With the series motor, however, the initial current-rush will depend entirely on the impedance of the motor circuit.

Commutation of current-rush. The large current due to a current-rush has to be commutated under unfavourable conditions, as, even if the machine is fitted with commutating poles, the commutating flux cannot follow instantaneously the rapid changes in the armature current. Therefore sparking is liable to occur at the brushes, but the operation of the motor may be considered as satisfactory provided that this sparking does not produce a flash-over (which is caused by an arc, formed between brush and segment, being drawn out across the commutator until it extends either from brush to brush or from a high-potential brush to the earthed frame in the vicinity of the commutator, thereby causing practically a short-circuit across the brushes).

To produce a flash-over, sufficient voltage must exist between adjacent commutator segments so that an arc, once formed between a brush and a segment, will be maintained and extended from segment to segment as the commutator rotates.

Under normal operating conditions the voltage between adjacent segments around the commutator depends on the flux distribution in the air-gap ; the voltage between segments in the vicinity of the brushes being influenced largely by armature reaction.

With current-rushes, however, E.M.Fs., in addition to the E.M.F. generated by rotation, are induced in the armature winding. For instance, the variation of current in the armature winding induces therein an E.M.F. (of self-induction), the magnitude of which, at any instant, is proportional to the rate of change of the flux produced by the armature current. Due to the lamination of the main-pole faces, the E.M.F. induced in the coils under the main poles will have a higher value than that induced in the coils in the neutral zone. Moreover, with an increasing current, the direction of the induced E.M.F. is the same as that of the E.M.F. generated in the armature by its rotation in the main flux.

Again, in the case of a series motor, another E.M.F. (which may be called the *transformer E.M.F.*) is induced in the armature winding due to the rate of change of the main flux.* This E.M.F. attains its maximum value in the coils occupying the neutral zone—since the magnetic axis of the coils coincides with that of the inducing field—and is zero in the coils at right angles (magnetically) to this position, the sum of the E.M.Fs. induced in the coils of each circuit of the armature winding being zero. Hence this variation of the main flux affects the distribution of potential around the commutator, but does not affect the E.M.F. between the brushes. With an increasing current the direction of the transformer E.M.F. induced in the coils under the leading pole-tips is the same as that of the E.M.Fs. due to rotation and self-induction. Under these conditions the distribution of potential around the commutator may be such that relatively high voltages occur between segments in the vicinity of the brushes.

Generally the current-rushes due to pressure-rises are not so severe upon commutation as those due to the restoration of full voltage following a brief interruption.

The series motor, as designed for traction service, even without auxiliary commutating devices, is able to withstand sudden pressure-rises of a large amount (perhaps 60 to 70 per cent, or more, above normal voltage), which, if applied to a shunt motor, designed without compensating windings, would certainly produce flash-overs; the motor will also operate satisfactorily with interruptions in the supply circuit such as occur in service, and in order to produce a flash-over under these conditions a voltage of from 50 to 80 per cent above normal is required. Of course, with a rough commutator or weak brush pressure, in combination with vibration, flash-overs may be produced with lower voltages, especially when the machine is running at high speeds.

Thus, from electrical as well as dynamical considerations, the series motor is, for tramway and suburban railway service, superior to both the shunt motor and the compound motor.

Special features in the electrical design of traction motors. For a series motor, without auxiliary commutating devices, to withstand pressure-rises and circuit interruptions without flashing-over it must be designed with—(1) a relatively "strong" field and a "weak" armature (i.e. the field ampere-turns at rated load must be much greater than the

* A similar E.M.F., due to transformer action, is present in single-phase commutator motors, see p. 89.

armature ampere-turns) ;* (2) a liberal number of commutator segments ; (3) a large neutral zone. In addition, solid spool bodies and short-circuited turns in the field spools must be eliminated, so that the growth of the flux may not be retarded by eddy-currents induced in these parts. These features must also be present, though not to the same degree, in commutating-pole machines, as if an attempt is made to utilize the full advantages of the commutating poles (e.g. by adopting a " strong " armature, a " weak " field, and a high average voltage per segment) the result will be a motor sensitive to pressure-rises and circuit interruptions.

The introduction of **commutating poles** into traction motors, however, enables a lower ratio of field ampere-turns to armature ampere-turns to be adopted than is possible with non-commutating-pole designs, and, as a consequence, the commutating-pole motor can be built with a lower flux and a higher speed than its predecessor. The lower flux densities result in lower core losses, which lead to improved efficiency, heating, and service capacity.

Other important **advantages of commutating-pole traction motors** are—

(1) Sparking at the brushes is practically eliminated at all loads and speeds, thereby enabling a non-abrasive brush, of low contact resistance, to be used on grooved commutators. Under these conditions the wear of the commutator and brushes is considerably less than that with non-commutating-pole motors, while the losses at the commutator are lower, thereby enabling a slight reduction to be made in the length of the segments.

(2) A range of economical running speeds is possible by " tap-field " or " shunted-field " control, by means of which different field strengths can be obtained for a given armature current. This method of control not only results in a lower energy consumption for a given service, but also increases the flexibility of the equipment. For instance, cars equipped for tap-field control can be operated economically on services differing considerably in schedule without any change in the equipment.

(3) Since perfect commutation is obtained, the average voltage between commutator segments may be higher than that in machines of the non-commutating-pole type, and, in consequence, the motors can be built for higher voltages. In fact, the development of high-voltage direct current traction has only been made possible by the commutating-pole traction motor.

(4) The tendency to flash-over is much less in a commutating-pole motor of good design than in a non-commutating-pole motor, owing normally to the low voltages between the segments in the vicinity of the brushes.

Therefore the commutation of current-rushes will be better than in non-commutating-pole machines. Generally the flash-over voltage of a commutating-pole motor will be from 25 to 30 per cent greater than that of a non-commutating-pole motor.

Other important electrical features which require consideration are the armature winding, the number of poles, and the number of brush sets.

* In non-commutating-pole traction motors the field ampere-turns at the rated load are from one to three times greater than the armature ampere-turns, whereas, in stationary motors, values between 1·5 to 1·75 are usually adopted.

Armature winding. A two-circuit (wave) armature winding is employed universally for tramway and railway motors when the output does not exceed 500 h.p. For larger outputs a multiple-circuit lap winding with equalizing connections is necessary.

The properties of the two-circuit winding which render it especially suitable for traction motors are (1) the two circuits of the winding are always electrically balanced, even when the magnetic circuits are unbalanced due to unequal air gaps ; (2) no equalizing circuits are required ; (3) multipolar machines can be operated with only two sets of brushes.

The two-circuit winding, however, possesses certain peculiarities with respect to the number of commutator segments and slots. Thus for a symmetrical winding the number of coil sides per slot cannot be a multiple of the number of poles ; with four poles the number of commutator segments and slots must be odd, but with six poles the number of commutator segments and slots may, under suitable conditions, be either odd or even. These peculiarities are due to the fundamental conditions which govern the application of wave windings, and are expressed in the equation

$$2C = py \pm a \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

where $2C$ is the number of coil sides, C the number of coils (and also the number of commutator segments), p the number of poles, y the average winding pitch (i.e. the mean of the front and back winding pitches, expressed in coil-sides), and a the number of circuits.

With two circuits we have

$$C = \tfrac{1}{2}py \pm 1 \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14a)$$

Hence for $p = 4, \quad C = 2y \pm 1,$

and for $p = 6, \quad C = 3y \pm 1.$

Therefore, since y can only have integral values (which may be either odd or even), C must be odd when $p = 4$, but may be either odd or even when $p = 6$. (NOTE.—For $p = 6$, C is odd when y is even and vice versa.)

Again, for a symmetrical winding the ratio C/S (i.e. the number of commutator segments per slot, where S is the number of slots) must always be an integer, and since S must be a whole number, therefore, when $p = 4$, C/S cannot be a multiple of 4, and when $p = 6$, C/S cannot be a multiple of 3.

Hence, if, with a four-pole machine, four or eight coil-sides per slot are to be employed, all slots cannot be filled with active conductors, and one or two dead, or dummy, coils must be inserted in certain slots to act as fillers. The dissymmetry in the winding will affect the commutation, but, except in cases where the number of slots per pole is small, quite satisfactory commutation is obtained when the winding contains one dead coil. Usually, however, with traction motors a small number of slots per pole is chosen, and therefore symmetrical windings (without dead coils and with three or five coils per slot) are employed.

Number of poles. Four poles are employed universally for tramway motors and the smaller railway motors for motor-coach trains. In these cases the overall diameter of the motor and the diameter of the armature core are somewhat severely restricted by the diameter of the driving

wheels (which, on tramcars, may be from 26 in. to 33 in., and on motor-coach trains may be from 36 in. to 43 in.). With the larger axle-mounted motors for locomotives the space restrictions (in so far as they affect the armature diameter) are usually not so severe as those on tramcars and motor-coach trains, and, therefore, a six-pole design may be possible, which may be more economical with respect to utilization of material than a four-pole design. The six-pole design is particularly desirable and, in fact, necessary for narrow-gauge locomotives on account of the smaller proportion of axial length occupied by the commutator and the end connections of the armature winding.

Number of brush sets. With tramway motors and the smaller railway motors it is customary to provide only two sets of brushes, and to locate them in such a position that the brushes can be inspected from the car floor. With larger locomotive motors the full number of brush sets are usually employed, both to shorten the commutator and to obtain better commutation than would be possible if only two sets of brushes were provided.

Features affecting the mechanical design of traction motors. Motors for tramway and suburban railway services* require mechanical features differing considerably from the standard practice with stationary motors.

Thus (1) the motors are located under the car floor in order to obtain a level floor ; (2) the power is transmitted through spur gearing in order that the speed of rotation of the armatures may be higher than that of the car axles, thereby enabling a motor of relatively light weight to be employed ; (3) the location of the motors under the car necessitates a completely protected design and imposes physical limitations upon the overall dimensions ; (4) the rotating parts must be capable of withstanding the large centrifugal forces corresponding to the maximum speed of the car or train.

These requirements necessitate the exclusion of cast iron from the construction of the motor, and the use, instead, of cast steel and malleable iron. For example, the frame, frame heads, commutator-shell, and clamping rings are of cast steel, while the armature end-flanges are of either malleable iron or cast steel.

Constructional Details

Frames.—Two types of frames were formerly in use, viz. (1) the split frame, (2) the box or solid frame, but present-day practice is towards the standardization of the box frame. Views of typical motors are given in Figs. 14, 15, 16.

A split-frame is necessary when provision must be made for inspecting and changing the armature or bearings without dismantling the motor from the truck. The lower half of the frame is arranged to open downwards so that the armature can be handled in an inspection pit. But a split frame is, for equal strength, heavier and less rigid than a box frame, and is difficult to keep oil-tight at the joint near the axle bearings.

Box frames, owing to their advantages over split frames, are now adopted for modern tramway and railway motors. This supercession of the split-frame tramway motor has been possible on account of the

* Motors for locomotives and trolley buses are discussed later (page 79).

increased reliability of commutating-pole motors and the introduction of improved methods of lubricating the armature bearings. Moreover, the extensive use of low-floor cars, requiring small wheels of 26 in. diameter

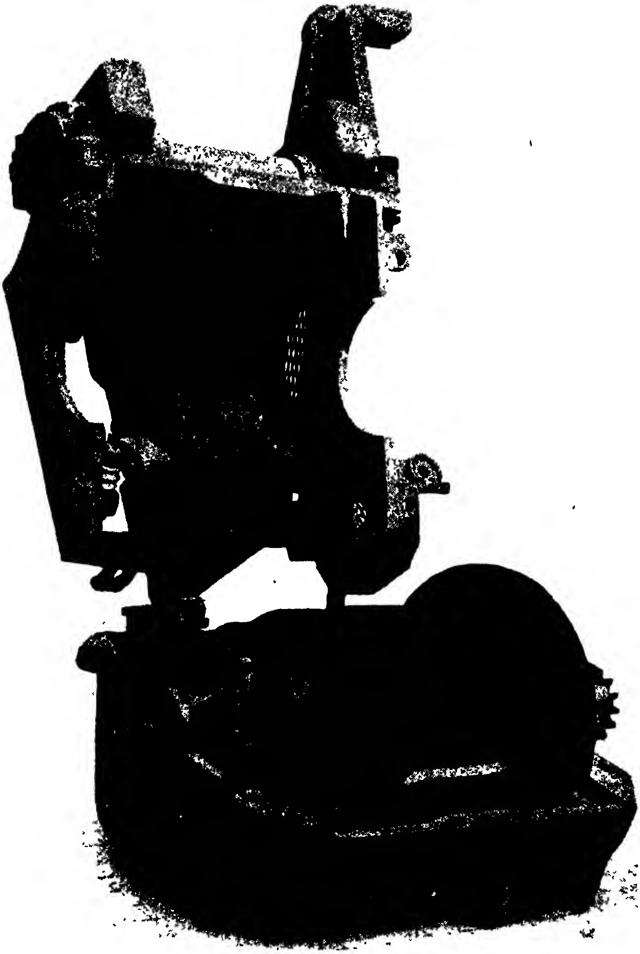


Fig. 14.—Split-frame Tramway Motor (English Electric Co.).

and the demand for light-weight cars, necessitate a box-frame motor (i.e. one having a maximum output for a given weight and space).

The removal of the armature from a box-frame motor necessitates the removal of the motor from the truck and the use of special

tools.* With single-truck cars the motor may be removed without removing the truck from the car, but with double-truck cars the removal of a motor usually necessitates the removal of the truck from the car.

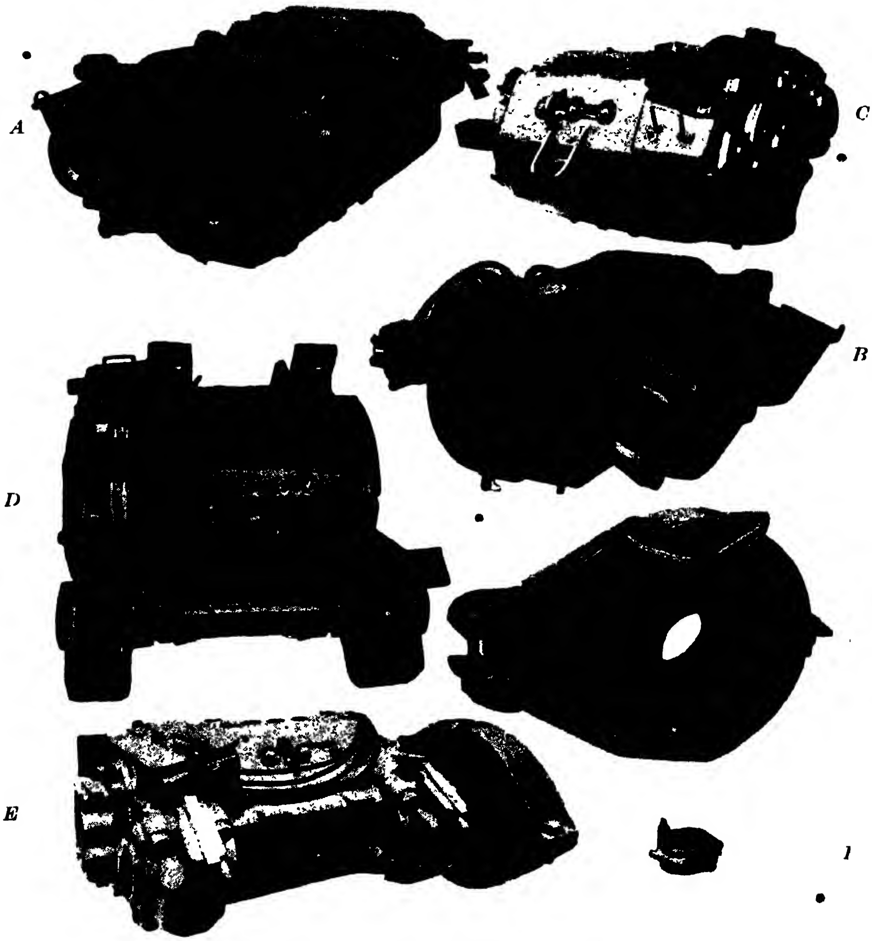


FIG. 15.—Box-frame Tramway Motors. *A*, *B*, B.T.-H. Motors; *C*, *D*, *E*, Metropolitan-Vickers Motors; *F*, Welded Sheet Steel Gear Case; *G*, Axle Collar.

The **armature bearings** are located in frame-heads or housings which, in split-frame motors, are carried in cylindrical seats between the two halves of the frame, and in box-frame motors are bolted to recesses in the ends of the frame. The bearings are usually of the

* For description of these tools see *Electric Journal*, vol. 13, p. 491; vol. 14, p 204; *General Electric Review*, vol. 18, p, 908

babbitted-sleeve type, but roller bearings are now employed extensively for tramway motors.

With sleeve bearings the bearing linings are usually of brass, lined with a thin layer of babbit metal of such thickness that, in the event of the babbit metal running through overheating, there is no possibility of the armature fouling the pole faces.

The **lubrication** of sleeve-type bearings is generally on the pad principle, using wool-waste saturated with oil. Self-oiling rings, however, are employed for the larger sizes of railway motors, especially when the armature speed is high.

Methods of suspension. With a geared motor, the centre-line of the armature must be maintained parallel to, and at a fixed distance from, the axle of the driving wheels. This is accomplished by supporting one side of the frame on the axle by suitable bearings. The other side of the frame is supported from the truck, either by a "nose" on the frame resting on a bracket attached to the transom of the truck, or by a transverse bar (bolted to the frame) carried on springs from the side frames of the truck. The former method—called "**nose suspension**"—is adopted with railway motors, and the latter method—called "**bar suspension**"—is usually adopted with tramway motors.

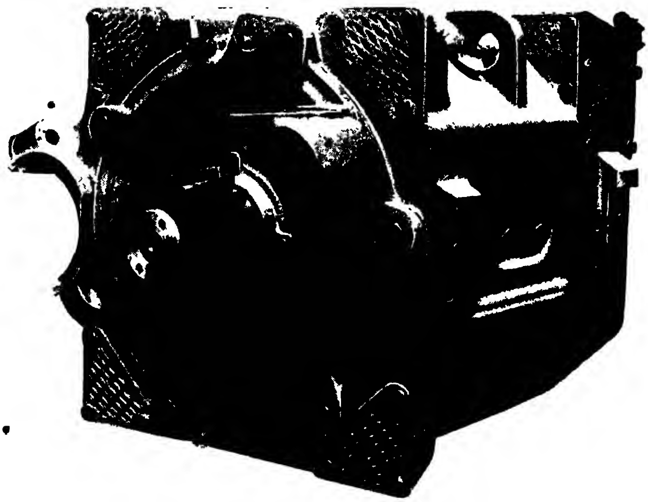
The **arrangement of a bar suspension** for a tramway motor is shown in Fig. 17. The suspension-bar rests upon "support" springs which are carried on each side frame of the truck; the bar and springs are maintained in position by two bolts passing through holes in each side frame, "reaction" springs being inserted between the head of each bolt and the underside of the side frame to restrict the upward movement of the bar. This illustration shows also the manner in which the motor is maintained in position on the axle when the distance between the wheel hubs is greater than the overall length of motor and gearing.

The **arrangement of a nose suspension** for a railway motor is shown in Fig. 18. The nose, *H*, on the motor is supported on a bracket, *F*, fixed to the transom, *B*, and the nose is prevented from rising by the strap, *G*. Auxiliary noses or safety lugs, *K*, are usually provided on the motor for the purpose of preventing the latter falling on to the track in the event of the suspension nose breaking. Under normal conditions these safety lugs are clear of the transom, but are supported on brackets, *E*, should the normal support fail. With locomotive motors the nose is usually spring supported.

Gearing. The usual method of transmitting power from the motor to the axle is through single-reduction spur gearing, the gear ratio being generally limited to a maximum value of $6\frac{1}{2}:1$. The maximum gear ratio is governed by the size of the wheels, distance between centres of axle and armature, and the smallest permissible size of pinion. The considerations involved in the selection of a suitable gear ratio for a given equipment and service are discussed in Chapter XIX. Generally, for a given motor and size of wheel a higher gear ratio will be required for city service than for suburban service.

A single set of gearing is adopted for motors up to about 300 h.p., but where larger motors are used on electric locomotives it is necessary

B



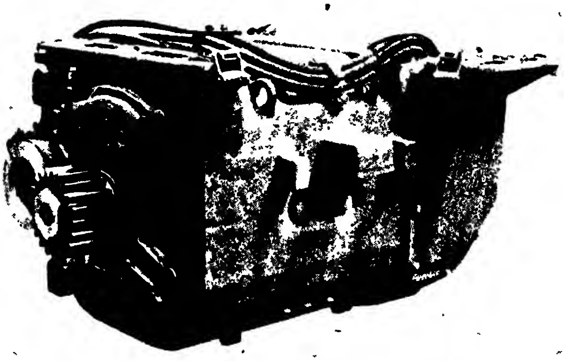


FIG. 16.—Typical Self-ventilated Railway Motors for Motor-coach Service.

A, **G.E.C. motor fitted with axle guard and supports for central collector shoe;** ***B***, **English-Electric motor (for narrow gauge) fitted with roller bearings and helical gearing;** ***C***, **B.T.-H. motor.**

NOTE.—Motors ***A***, ***C*** **have oil-pad lubrication for the armature bearings, hooded inlets (at commutator end) for the cooling air, and screened outlet openings. Motor** ***B*** **has screened inlet and outlet openings.**

to adopt twin gears in order to obtain uniform pressure on the gear teeth. When this method of driving is adopted springs are fitted between the rims and hubs of the gear-wheels to equalize the loads on the gear teeth at each end. Incidentally, the springs relieve the teeth from shocks due to impacts, between wheels and rails, caused by irregularities in the track.

The **pinion** is usually of alloy-steel, heat treated, and is fitted to a taper on the armature shaft. The width of face varies from 4½ in. to 7½ in., and the tooth pitch varies from 3¾ to 1¾ (diametrical).

The material of the pinion (as well as that of the armature shaft) and the form of tooth have to be given very careful consideration when small driving wheels are employed and relatively large outputs are required (e.g. 26 in. driving wheels and 50 h.p. output). For these cases a case-hardening nickel-steel is employed, the surface of the teeth being hardened (after cutting) to an index of 500–600 on the Brinnel scale. The form of tooth is a " corrected " involute having a longer addendum than the standard involute form. In consequence the tooth is much stronger than an ordinary involute pinion tooth and a larger arc of action is obtained, together with less sliding action in the arc of approach.

The **gear-wheel** is of forged alloy-steel, heat treated, and is pressed on to the axle.

During recent years the manufacture of gearing for traction service has received considerable attention, and, in consequence, gearing of high quality and long life is now obtainable. The principal feature in the manufacture of modern gearing is the process of heat treatment to which the gears and pinions are subjected in order to obtain teeth with a hard surface and a tough centre. With some processes, a surface of exceptionally hard tool-steel is obtained, having a thickness of from ⅛ in. to $\frac{3}{16}$ in. The heat treatment is, of course, given after the machining operations have been completed.

The advantages of heat treatment, in connection with gearing, will be apparent from an examination of Table VI, in which the properties of gearing, with and without heat treatment, are compared.

The **gear-case** is either of malleable cast iron or of welded sheet steel, and is supported from lugs or brackets on the frame of the motor. Examples of both are shown in Figs. 15, 16.

Armatures. The conditions under which traction motors operate demand a thoroughly sound mechanical construction of the armature, as well as means for replacing a shaft without disturbing either the winding or the commutator. With railway motors it is possible, in a number of cases, to adopt a spider construction for the armature core, but with the smaller armatures of tramway motors there may be insufficient room for a spider. In this case the armature laminations must be assembled on the shaft and held between end-flanges fixed to the shaft. By suitable design, however, it is possible to remove the shaft without disturbing either the core or the commutator. For instance, if the commutator is fitted to an extension of the front end-flange, and the latter is provided with a number of tapped holes, opposite to corresponding holes in the core and back end-flange, bolts may be inserted through the latter (after the oil deflector has been removed) and screwed into the tapped holes, thereby holding the core tight while the shaft is pressed out.

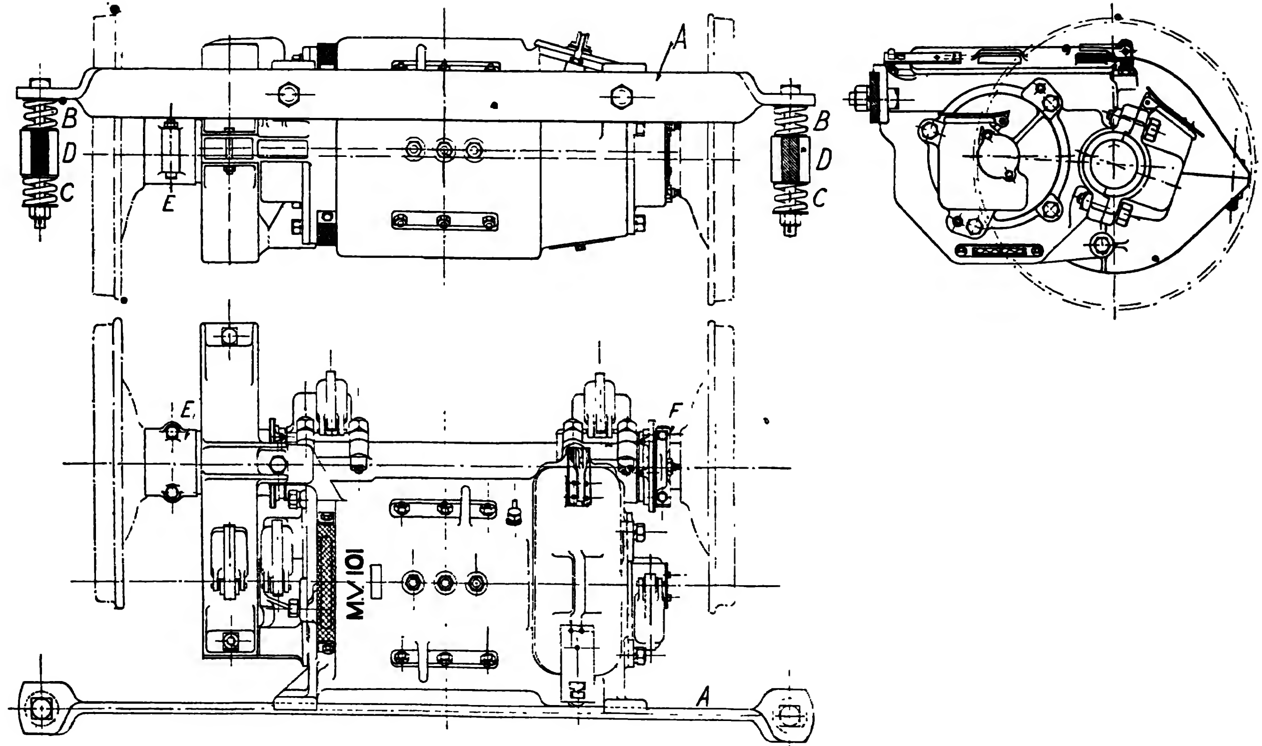


FIG. 17.—Arrangement of Bar Suspension (Metropolitan-Vickers).
A suspension bar; *B*, supporting springs; *C*, reaction springs; *D*, side frame of truck; *E*, non-adjustable axle collar *F*, adjustable axle collar.

TABLE VI

Comparative Properties of Various Grades of Gearing.

Grade.	Heat Treatment.	Remarks.	Ultimate Tensile Strength.	Elastic Limit.	Elongation (2-in test piece).	Reduction in Area.	Relative Hardness.	Relative Average Initial Cost.	Relative Life of Gears (based upon guaranteed figures).
			tons per sq. in.	tons per sq. in.	per cent.	per cent.	Brinell scale.		
Cast steel.	None.	Medium carbon.	27–32	11–15	18–20	20–30	121–155	1·0	1·0
Forged steel.	None.	Medium carbon.	31–38	16–20	18–20	35–45	176–196	1·1	1·25
Forged steel.	Oil tempered.	High carbon. Uniform structure throughout.	49–54	36–38	10–15	25–35	300–360	1·4	2·5
Forged steel.	Special.	Medium carbon. Uniform structure throughout.	62–67*	62–67*	..	..	420–600	2·0	3·5
Forged steel.	Special.	Hardened high-carbon surface. Tough low-carbon core.	Cannot be determined, as structure of metal after treatment does not allow a test piece to be obtained.				555–650	2·0	5·0

* Obtained from treated test bars.

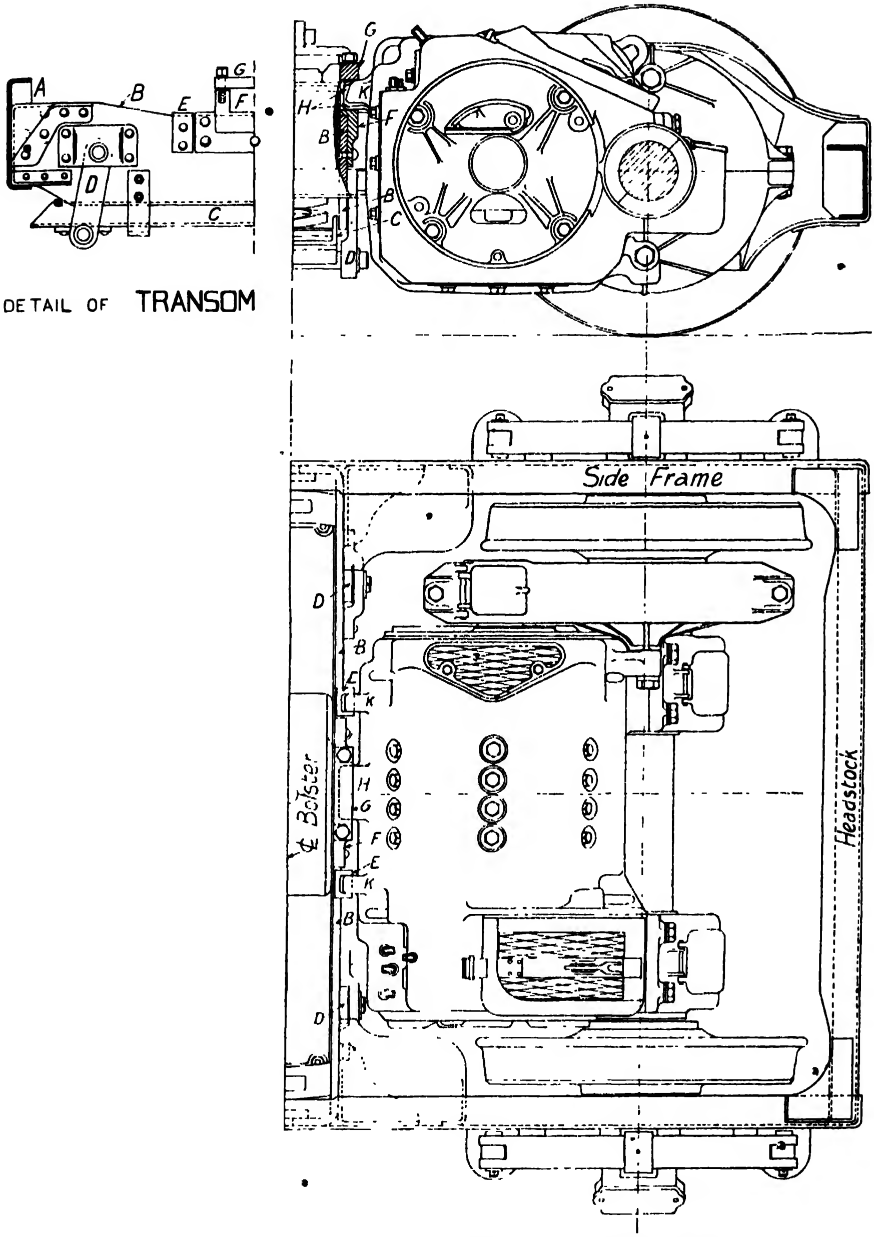


FIG. 18.—Arrangement of Nose Suspension for Railway Motor.
NOTE.—The motor is shown in position on the truck, and a detail of the transom is given. (British Thomson-Houston Co.)

A, Side frame of truck; *B*, transom; *C*, spring-plank (from which the springs supporting the bolster are carried); *D*, swing-links (for carrying the spring-plank); *E*, brackets for supporting safety lugs, *K*; *F*, bracket for supporting nose, *H*; *G*, strap; *H*, nose; *K*, safety lugs.

Modern motors are of the ventilated type, with an *axial* flow of the air, so that it is necessary to provide *longitudinal* ventilating ducts in the core, end-flanges, and commutator. The **ventilating ducts** in the core usually consist of a number of holes in order to obtain a large cooling surface. With self-ventilated motors the ventilating fan is fixed to the back end-flange. Typical fans are shown in Fig. 20.

The **armature winding** of tramway motors and the smaller railway motors is exclusively of the two-circuit variety, and the coils are located in open slots in the punchings. Two or more turns per coil are usually necessary for tramway-motor armatures, but single-turn coils are employed for low-voltage (600 V.) railway-motor armatures. When one or two turns per coil are adopted the conductors consist of copper bar, and in these cases the insulation consists principally of mica. To prevent slackness in the slots, the slot portion of the coil is formed to the exact size of the slot in a steam-heated press and, after winding, temporary

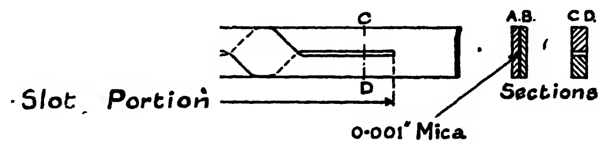


Fig. 19.—Diagram of Double Cross-over in Armature Bar.

binding bands are applied with the armature hot, so as to force the coils firmly into the slots. These bands are removed when the armature is cold and replaced by permanent binding bands.

The **number of coils per slot** is usually either three or five, although, in some cases, four and six coils per slot are used ; but these numbers, in a four-pole machine, require dead coils. When five coils per slot are adopted in large railway motors, the slots become wide, and, at high flux densities in the air-gap and armature teeth, eddy-currents may be generated in the conductors. Some manufacturers provide against this by splitting the slot portion of the conductor and introducing a double twist or cross-over, as represented in Fig. 19.

The **end connections** of the coils are usually protected from dust and oil by hoods or coverings of canvas, which are bound into place after the winding has been completed.

The **binding bands** are an important item on account of the high peripheral speeds (approaching, in some railway-motor armatures, 8000 ft. per min) and the large centrifugal forces to which the armature winding is liable to be subjected. The tinned-steel binding wire is applied under considerable tension, and the bands are retained in position by clips of tinned copper. The ends of the clips are bent over and sweated to the binding wires, which are also sweated to form a continuous band. Usually the clips are inserted at intervals and the ends envelop only the end portions of the binding bands, as shown at *A*, Fig. 20. Some manufacturers, however, employ continuous clips with serrated ends, which, when bent over, envelop the whole of the band of binding wire, as shown at *F*, Fig. 20.

Typical armatures for tramway, motor-coach, and locomotive services

are shown in Fig. 20. Armatures *C* and *D* are for large, forced, ventilated, 1500-volt motors, and are fitted with fans for the purpose of ensuring an efficient circulation of air through the armature core. Armature *D* is of interest as it has a lap winding and bakelite slot wedges, so that no binding bands have to be placed over the core.

Commutator and brush-gear. The commutator for a tramway motor is similar in construction to that for a stationary motor, i.e. the back V-ring is solid with the shell, and the front V-ring is held in position by a recessed ring nut (see Fig. 24). With railway motors, however, the commutator must be designed to accommodate the internal projecting portion of the frame-head carrying the commutator-end armature bearing, and special precautions must be taken to prevent oil reaching the interior. The shell and *front* V-ring are therefore combined, while the back V-ring is held in position by bolts, as shown in Fig. 29. The mica between the segments is recessed to a depth of $\frac{3}{64}$ in. to eliminate commutation troubles due to "high mica."

The **brush-holders** are fixed to mica-insulated supports which are bolted to machined seats on the frame. The brush-holders are arranged for radial adjustment and also means for adjusting the brush pressure.

Illustrations of modern brush-gear are given in Fig. 21. The brush-box is fitted with an enclosing cover to prevent ingress of road grit (which may be drawn into the motor with the ventilating air) to the brush-box, thereby avoiding the possibility of side wear of the brushes.

The **brush pressure** required for a traction motor is greater than that necessary for stationary motors, on account of the increased vibration. For motors operating at low speeds, over good track, a brush pressure of from 2 to 3 lb. per sq. in. is satisfactory, but for high speeds the pressure must be increased to about 5 lb. per sq. in.

Poles and field coils. The main poles are built of soft steel laminations; the commutating poles are solid steel forgings.

The **field coils** for the main and commutating poles are former wound, the conductor consisting either of rectangular wire, insulated with asbestos and cotton coverings, or of flat copper strip insulated between turns with asbestos tape. The coils are generally "mummified"—that is, impregnated with a bitumen compound—to obtain a coil of good thermal characteristics, combined with non-hygroscopic properties.

With **motors for tap-field control** each coil of the main-field winding must be wound in sections, two sections being necessary when two speeds—corresponding to a given armature current and voltage—are required, and three sections when three speeds are required. The corresponding sections of each coil are connected to form a series-group, and the two, or more, groups are connected in series, tappings being brought out from the junctions of the groups. The armature and commutating coils are connected to form a separate series-group in order that the direction of rotation may be controlled. Thus, a two-speed box-frame motor will have five terminal leads (viz. one armature lead, one commutating-field lead, and three main-field leads).

A diagram of the **internal connections** of a two-speed motor is given in Fig. 22.

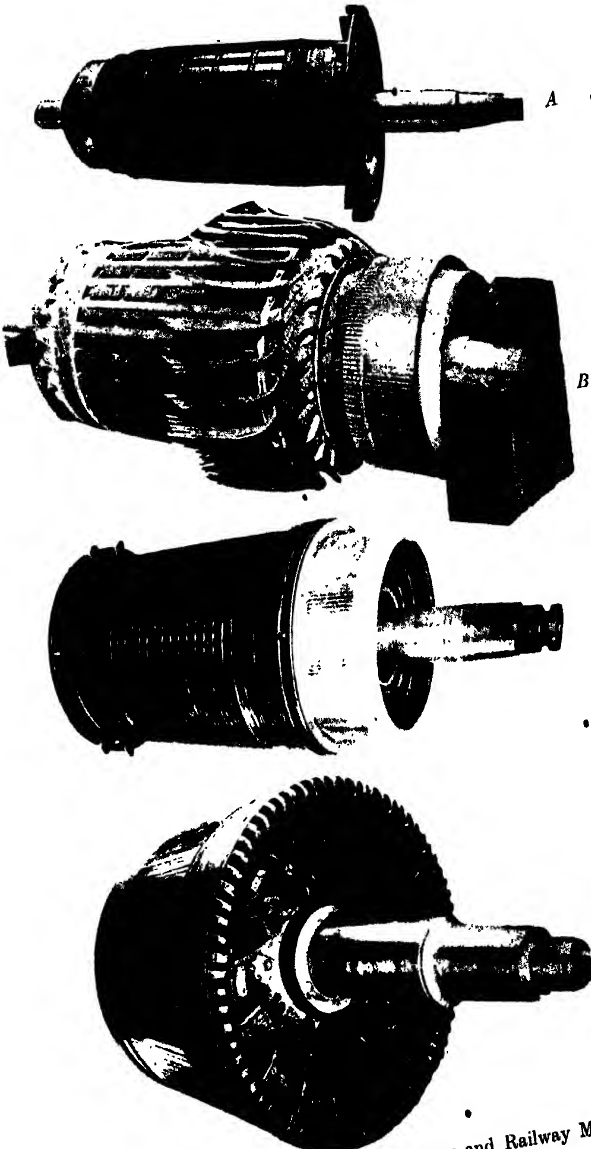


FIG. 20 (*Part*).—Armatures of Tramway and Railway Motors (Metropolitan-Vickers).

A, *B*, tramway motor armature, complete and in process of winding; *C*, armature for high-speed passenger locomotive; *D*, armature for freight locomotive. NOTE.—Armature *D* has a lap winding with equalizing connections, and the slots are closed with bakelite wedges, so that no binding bands are required over the core.

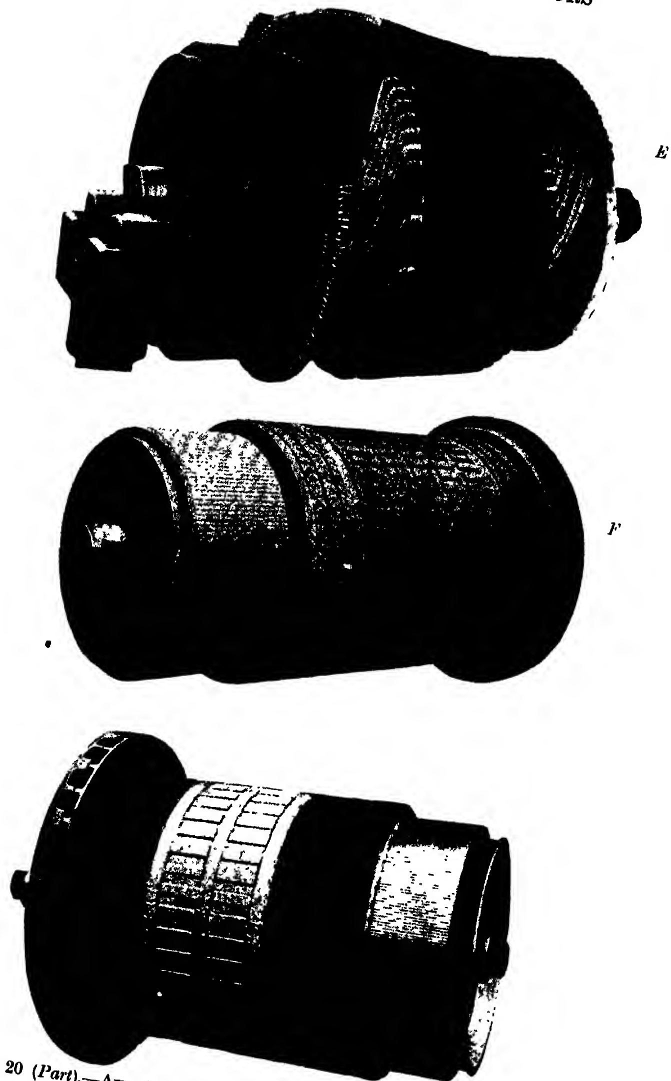


Fig. 20 (*Part*).—Armatures of Railway Motors (General Electric & English Electric Cos.).

E, armature for high-speed passenger locomotive in process of winding; *F*, *G*, armatures of self-ventilated motors for motor-coaches. Note.—Armature *G* is for narrow gauge and runs in roller bearings.

The **general arrangement** of the poles, field coils, connections, and brush-gear of modern tramway and railway motors is shown in the interior views of Figs. 14, 31, and the longitudinal and cross-section drawings of Figs. 23, 24, 28, 29.

Ventilation. The modern commutating-pole traction motor requires artificial cooling in order to obtain the full advantages of the commutating-pole design, as with natural cooling the rating of the motor would be considerably below that which would be possible from the commutation standpoint. The ventilation may be effected either by means of a fan, fixed to the back of the armature, in conjunction with longitudinal ventilating ducts and suitable openings in the frame—such a machine being known as a **self-ventilated motor**—or by means of an external

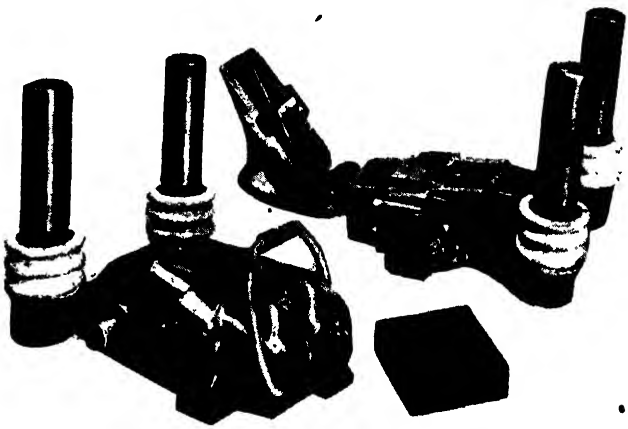


Fig. 21.—Metropolitan-Vickers Enclosed Brush-gear for Tramway Motor.

blower in conjunction with suitable air ducts and openings in the frame of the motor—such a machine being known as a **forced-ventilated motor.** The latter system of ventilation is used principally with motors for locomotive service as, in this case, all motors on the locomotive may be ventilated by means of a single blower, which can deliver a large quantity of air at the required pressure.

The advantages of forced ventilation are—(1) the quantity of air may be adjusted, if desired, within limits ; (2) the supply of air to the motors is not affected by the speed of the latter, so that efficient cooling takes place during the whole period that the motors are in service ; (3) a blower is more efficient for ventilating purposes than a fan fixed to the armature shaft, especially when a large quantity of air is required.

For tramway and motor-coach railway services, however, a self-ventilated motor possesses advantages over a forced-ventilated motor, as the former is self-contained and the fan adds very little weight to the equipment, whereas with forced-ventilated motors an external blower with distributing air ducts would be required on each motor-coach. In this case the weight of the ventilating equipment, combined with the

extra capital and maintenance costs, would entirely outweigh the advantage in the system of ventilation.

The air may be circulated through the motor on either the series system or the parallel system, the latter being employed in all present-day designs of self-ventilated motors. In all cases a sufficiently high air velocity must be employed to prevent the deposit of dust in the ventilating ducts.

Fig. 24 shows the application of the parallel system of ventilation to a box-frame tramway motor. The air enters through openings at the commutator end of the frame and passes through the motor in two parallel paths—one being external to the armature, and the other internal to it, via the ventilating ducts—the air from each path being expelled through the fan and the openings in the pinion-end of the frame. A baffle plate prevents the air being returned by the fan to the interior of the motor. In the motor shown in Fig. 24 a single fan is employed, and the fan blades extend over the back-end of the armature winding. In some cases, e.g. in the motor illustrated in Fig. 14, a double fan of the box type is employed.

The position of the air inlet openings should be such as to avoid, as far as possible, the direct ingress of road grit and brake-shoe dust. Road grit causes unnecessary wear of the brushes, and brake-shoe dust not only provides a conducting path when deposited upon the surfaces of insulators, but is inflammable when ignited by a spark or a flash-over. When practicable, therefore, the inlets should be fitted with hoods, examples of which are shown in Fig. 16.

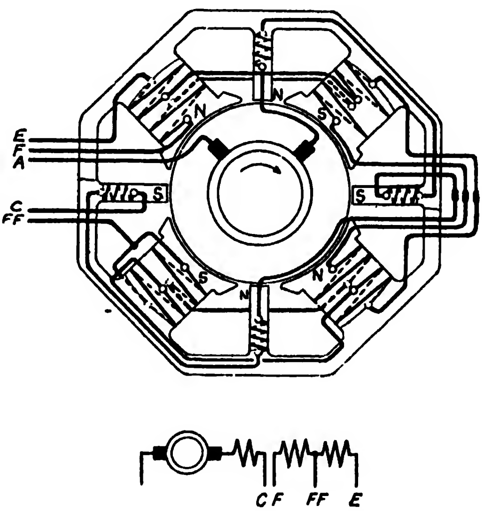


FIG. 22.—Internal Connections of Split Frame, Commutating-pole Tramway Motor arranged for Tap-field Control. NOTE.—The main-field coils are wound in two equal sections.

The **forced system of ventilation** as applied to a large twin-geared locomotive motor is shown in Figs. 29, 30. The air is supplied to each pair of motors through the hollow centre bearing on the truck frame; it enters each motor through a large rectangular opening at the commutator end, and is expelled through openings in the frame and back-end frame head. The ventilating ducts in the armature core consist of a number of tunnels 1 in. in diameter.

RATING

The rating of an electrical machine has usually some connection with the nature of the load or duty-cycle on which the machine has to operate, e.g. industrial motors which run continuously under practically steady

loads are rated on a continuous load basis, the rated load being defined as the output which the motor will develop continuously with a specified temperature rise. But with tramway and suburban railway services the duty-cycle consists of irregular cycles of variable output, a typical cycle being represented in Fig. 25. The irregularity of the load-cycle is influenced not only by normal and known variables, such as the variable distance between stations, gradients, etc., but also by abnormal and

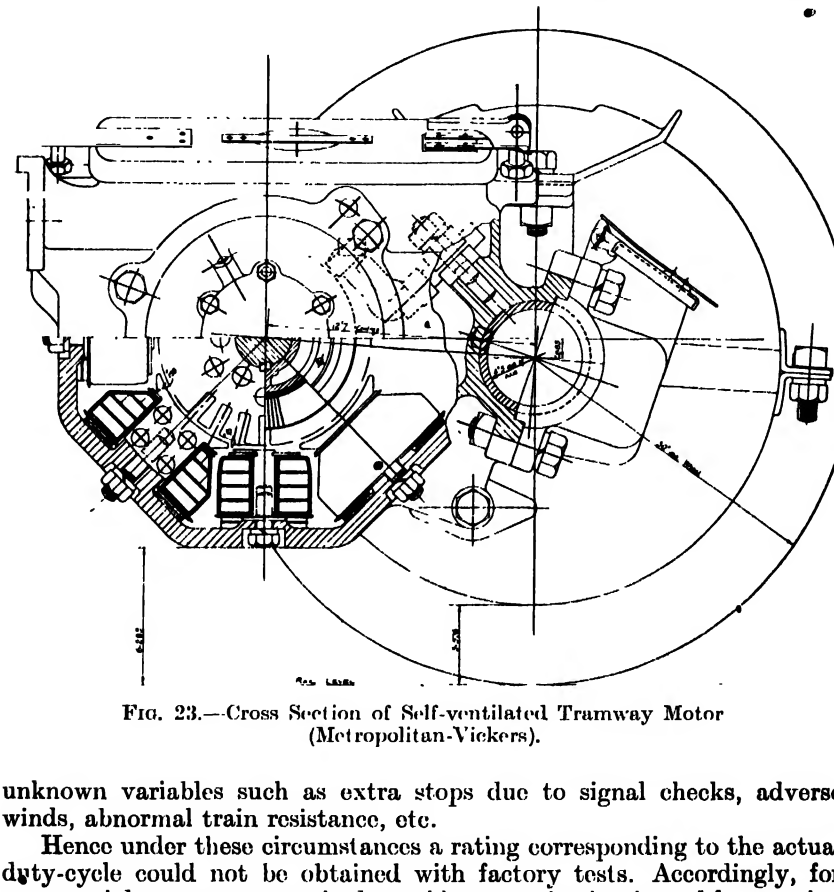


FIG. 23.—Cross Section of Self-ventilated Tramway Motor (Metropolitan-Vickers).

unknown variables such as extra stops due to signal checks, adverse winds, abnormal train resistance, etc.

Hence under these circumstances a rating corresponding to the actual duty-cycle could not be obtained with factory tests. Accordingly, for commercial purposes, a nominal or arbitrary rating is adopted for traction motors, and is based on the one-hour load (at normal voltage) which will produce a temperature rise of 100° C. (by resistance) when the motor is tested at the factory on a stand in the manner described in Chapter VII.

This method of rating was introduced in 1902 by the American Institute of Electrical Engineers,* and was at that time considered to represent, for commercial purposes, a fair method of comparing the performances of motors by means of a simple factory test, i.e. motors of

* See *Transactions*, vol. 19, p. 1803. The rules have been revised and extended from time to time, and the section relating to railway apparatus is given in the Appendix to this volume.

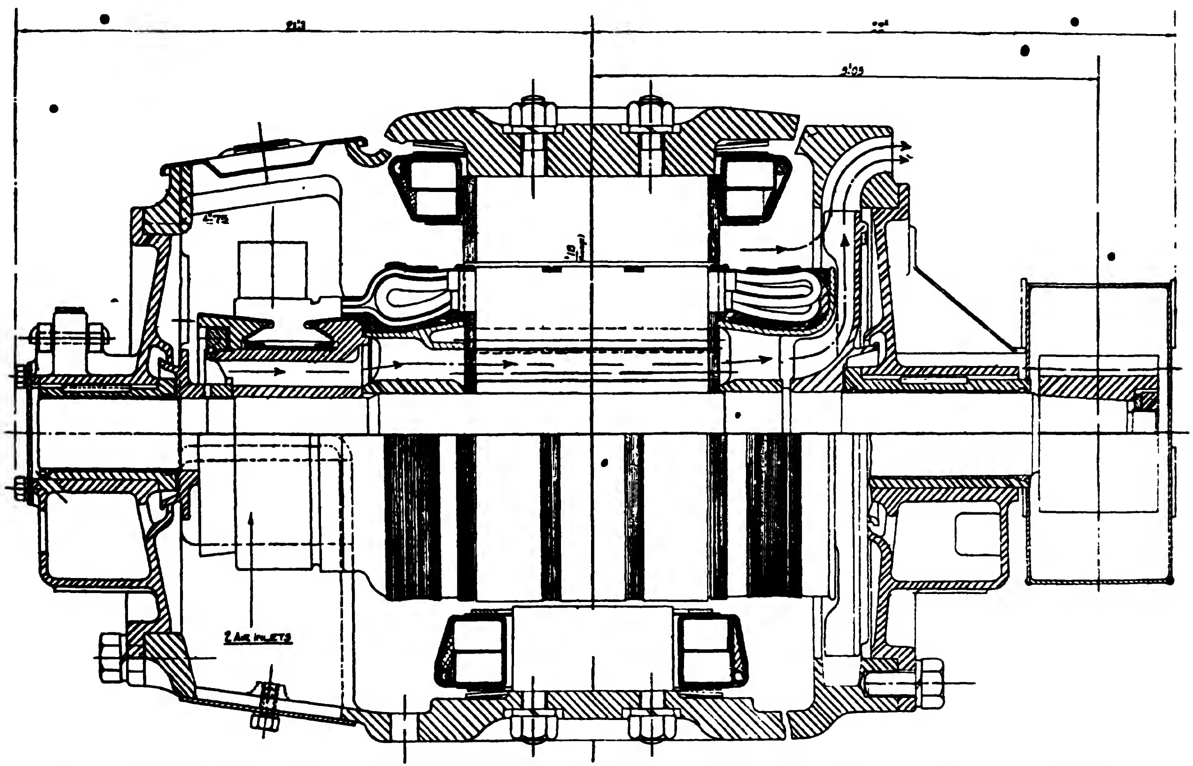


FIG. 24.—Longitudinal Section of Self-ventilated Tramway Motor (Parallel Circulation). (Metropolitan-Vickers.)

equal one-hour ratings were considered to be capable of operating similar services with approximately the same temperature rise. But with modern ventilated motors the one-hour rating gives no comparison between the service performances of motors. The one-hour test, however, imposes testing conditions which are sufficiently severe to ensure reliability of the motors in service, and for this reason it is retained at the present day.

The **temperature rise in service** depends principally upon the average losses in the motor under service conditions and the rate at which these losses can be dissipated. The former is influenced by the nature of the service and the design of the motor; the latter is influenced principally by the ventilation, and, with self-ventilated motors, is a function of the armature speed. Usually, for tramway and suburban service conditions, the temperature rise after a day's running is of the order of 65° C. This

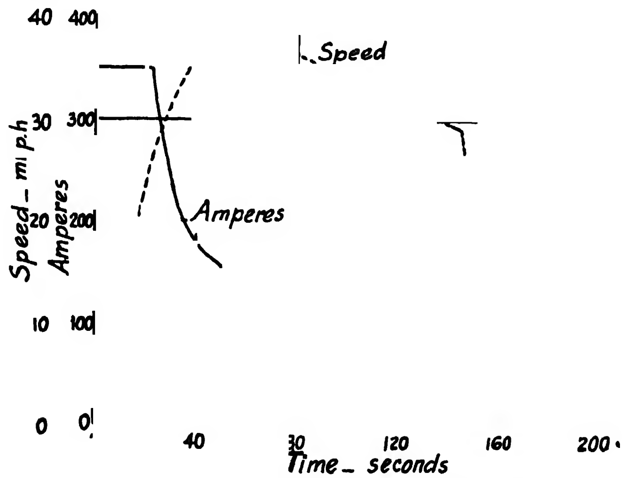


FIG. 25. -Traction Duty Cycle (Suburban Railway).

temperature rise is somewhat greater than that (40° C.) which is customary with industrial motors, as with traction motors space and weight restrictions necessitate a service performance as high as temperature conditions will permit. But, with the use of class B insulation (i.e. mica and asbestos)—for which the limiting hot-spot temperature is 130° C.—a temperature rise of 65° C. (by thermometer) under service conditions is well within the safe operating limit for this insulation.

Effect of ventilation on temperature rise and rating. With any electrical machine the rate of increase of temperature—due to the heat produced by the electrical and mechanical losses—depends upon two factors, viz. (1) the rate at which heat is stored in the mass of the machine, (2) the rate at which heat is dissipated by radiation, ventilation, etc. The temperature becomes constant when the heat produced is entirely dissipated by radiation and ventilation. The ultimate temperature rise at a steady load is, therefore, affected by the ventilation, but the temperature rise at the end of a run of short duration will be influenced largely by the thermal capacity of the machine.

Hence the one-hour rating of a traction motor is influenced more by the thermal capacity of the motor than by the ventilation, but the continuous and service ratings are influenced almost entirely by the ventilation, and will depend upon the volume of air which can be passed through the motor per minute.

For example, with a self-ventilated motor of the type illustrated in Fig. 14, the continuous output, at normal voltage, corresponding to a temperature rise of 75° C., is about 75 per cent of the one-hour rating. If, however, the lower outlet openings, Fig. 14, are closed with solid covers, instead of perforated covers, the continuous output for the same temperature rise is about 65 per cent of the one-hour rating, while if all ventilating openings are closed with solid covers so as to convert the motor into a true totally enclosed machine, the continuous output for the given conditions will be about 50 per cent of the one-hour rating.

The **volume of air** required to dissipate a given loss is easily calculated if the effects of radiation, etc., are ignored. Thus, taking the weight of 1 cub. ft. of air to be 0·076 lb. (or 34·5 grammes), the specific heat as 0·237, and the caloric to be equivalent to 4·2 watt-seconds, then the energy expended in heating 1 cub. ft. of air *0*° C. is

$$34{\cdot}5 \times 0{\cdot}237 \times 0 \times 4{\cdot}2 = 34{\cdot}30 \text{ watt seconds.}$$

Therefore, for a temperature difference of 20° C. between inlet and outlet, 1000 cub. ft. of air per minute will, theoretically, dissipate

$$34{\cdot}3 \times 20 \times 1000/(60 \times 1000) = 11{\cdot}4 \text{ kW.}$$

The practical limit to the volume of air which can be passed through a motor for cooling purposes is reached when the velocity of the air through the ventilating ducts is so high that the pressure required becomes excessive.

Effect of operating voltage on the rating. Motors for operating on high-voltage circuits require larger leakage surfaces at the commutator and brush-gear in addition to extra insulation on the armature and field coils. Due to the additional insulation on the coils, and the small size of conductor, the space-factors of the armature and field coils of a high-voltage motor will be lower than those of a similar armature and frame wound for a low voltage, e.g. 600 volts. Thus the rating of a given frame for a 600-volt motor will have to be reduced when it is wound for higher voltages. Generally a 10 per cent to a 15 per cent reduction in the 600-volt rating is necessary when the same frame is wound for operating directly on 1200-volt circuits.

In many, cases, however, two 750-volt motors are operated in series on 1500-volt circuits, each motor being insulated for 1500 volts, and by the use of high-grade insulation the rating of these motors can be made equal to that of standard low-voltage motors of similar dimensions.

Generally, for direct operation on high-voltage circuits, a new design of motor is desirable, in which the armature and commutator have larger diameters than those for a low-voltage motor of similar output.

Effect of wheel diameter and gauge on rating. With an axle-mounted motor, the size of motor, and therefore the rating, is limited by (1) the diameter of the driving wheels, (2) the gauge of the track rails. For a

given diameter of wheel the maximum vertical dimension of the motor is fixed by (*a*) the clearance between the bottom of the motor and the track, (*b*) the clearance between the top of the motor and the underside of the car floor. In deciding upon the minimum clearance between the bottom of the motor and the track, due allowance must be made for wear of the wheel tyres, as otherwise, with a large motor, the full wear may not be obtained from the tyres.

The **wheel diameter** is not usually a limiting feature on surface railways in this country (on which the standard wheel for motor-coach trains has a diameter of about 42 in.), but becomes a serious limitation on tube railways and on those railways abroad where the standard wheel diameter is 33 in. On the London tube railways the difficulty has been overcome by the use of 36 in. wheels on the motor trucks, together with a stepped floor above these trucks, the wheels on the other trucks being 26 in.

The **gauge** of the track rails has also a considerable effect on the rating of a motor for a given diameter of driving wheel, and narrow gauges restrict very considerably the output, especially when the wheel diameter cannot be increased to allow the use of a six-pole design.

When the whole distance between the wheel hubs is occupied by the motor and gearing, it is possible, with countersunk or roller armature bearings, and single gearing, to utilize about 75 per cent of this distance for the armature and commutator, the remaining 25 per cent being occupied by the gear, gear-case, and frame-heads.

NOTE.—An instructive paper, by Dr. F. W. Carter, dealing with the rating of traction motors is published in the *Journal of the Institution of Electrical Engineers*, vol. 65, p. 994.

CHARACTERISTIC CURVES

In Figs. 26, 26A are given characteristic curves of typical tramway and railway motors, showing the efficiency, speed, and tractive effort for a given gear ratio and diameter of driving wheels. These curves have been plotted in accordance with the standard method adopted for traction motors, and the manner in which the various quantities are determined and calculated is considered in detail in Chapter VII.

LOCOMOTIVE MOTORS

The constructional features of motors for electric locomotives are subject to more variation than those of motors for tramway and suburban railway service on account of the more varied operation of the electric locomotive. As electric locomotive operation is discussed in a later chapter, we shall for the present consider only the features which are peculiar to the locomotive motor and which differ from those common to the motor for motor-coach and tramcar service.

Except in the case of **light locomotives,** for which the standard geared motor, as used on motor-coach trains, is suitable, the motors are of larger output than those previously discussed, and in consequence modifications are necessary in the methods of transmitting the power to the driving axle and of mounting the motors. Moreover, the service conditions usually involve relatively long running periods, and therefore the motors must be selected on a continuous-rating basis. Again, owing to the facility with which forced ventilation can be applied to the motors and

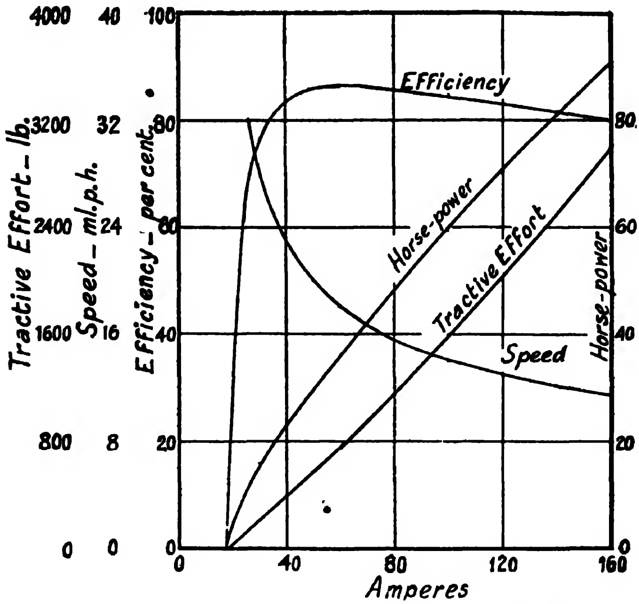


FIG. 26.—Characteristic Curves of B.T.-H. Tramway Motor (52 h.p., 525 volt, 820 r.p.m., 32 in. wheels, 5·21 : 1 gear ratio).

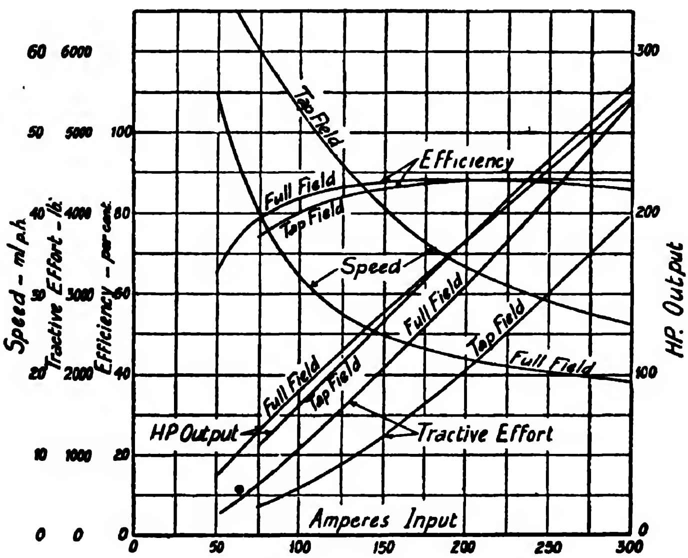


FIG. 26A.—Characteristic Curves of B.T.-H. Railway Motor (250 h.p., 775 volt, 500–700 r.p.m., 42 in. wheels, 3·18 : 1 gear ratio).

the advantages of this method of ventilation, the larger locomotive motors are always of the forced-ventilated type.

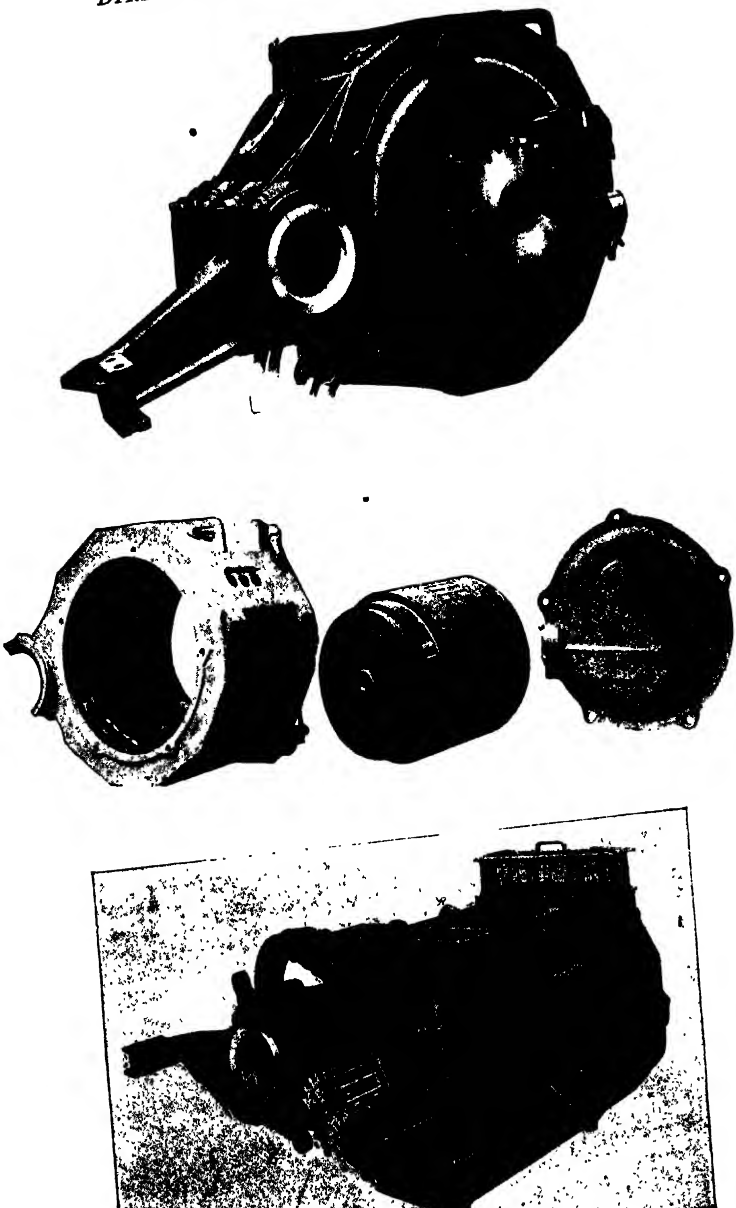
For **slow and medium-speed passenger and freight services** the geared axle-mounted motor with nose suspension is frequently employed, and two examples are shown in Fig. 27. These motors differ in a number of features from those illustrated in Fig. 16. For example, the armature bearings are lubricated by self-oiling rings, the motors are forced ventilated, and no fans are fitted to the armatures. The motors also differ from each other in their general design; one motor, *A*, being designed for narrow (3 ft. 6 in.) gauge, and the other, *C*, for broad (5 ft. 6 in.) gauge. Moreover, the air inlet is at the commutator end in one machine (*A*) and at the pinion end in the other machine (*C*). The narrow-gauge motor is a six-pole machine; its armature having a relatively large diameter and short core length. The broad-gauge motor (which is rated at 340 h.p., 500 volts, 665 r.p.m., and is insulated for 1500 volts) is a four-pole machine having an armature of relatively small diameter and long core length. In consequence, a relatively high speed of rotation can be employed together with a large gear ratio and driving wheels of small diameter. For example, the motor could be used with 44 in. wheels and a gear ratio of 4·94 : 1, although the locomotive on which it is installed (Reference No. 4, Table XII) has 51 in. driving wheels and a gear ratio of 4·94 : 1. Further details of the construction and general arrangement are shown in Fig. 28.

Attention is directed to the oil throwers and deflectors, the equalizing connections fitted to the armature winding (which is of the multiple-circuit type), and the yoke ring carrying the (four) brush sets.

When motors of large output are geared for low operating speeds, **twin gearing** (i.e. gears at each end of the armature shaft) may be necessary to obtain a more uniform and a higher working pressure on the gear teeth than would be possible with single gearing having a wide face. To equalize the pressures on the teeth of the twin gearing, the gear wheels are usually made with separate rims, which are connected to the centres or hubs by a number of springs. Alternatively, solid gears and spring pinions may be employed.

An example of this type of motor is shown in Fig. 29, and a view showing the motors in position on one of the trucks of the locomotive is given in Fig. 30. This view shows clearly the restricted space available for the motor frame and also the method of supplying the ventilating air to the motors (via the hollow centre bearing and transom of the truck).

For **moderate-speed and high-speed locomotives,** which are required to give considerable outputs at speeds between 40 and 80 ml.p.h., the power equipment may consist of either a number of motors (four or more) of moderate output (300–600 h.p.), or one, or more, motors of large output. In general, the use of geared, axle-mounted motors with nose suspension is undesirable for high-speed service on account of the relatively large unspring-borne weight which, with this type of suspension, would have to be carried on the driving axles. Geared motors, however, may be employed for this service, provided that the motors are mounted on the truck, or locomotive, framing. But a flexible transmission is then necessary, as relative motion between each armature



B

FIG. 27.—Axle-mounted Locomotive Motors.

A, English-Electric 325 h.p., 750-volt, motor for 3 ft. 6 in. gauge; *B*, Frame, armature and commutator frame-head of *A*; *C*, Oerlikon 340 h.p., 500-volt motor for 5 ft. 6 in. gauge.

shaft and driving axle must be permitted, owing to the locomotive framing being spring-supported from the axles.

The flexibility in the power transmission may be obtained in three ways—(1) by mounting the gear-wheel on a transverse shaft (called a

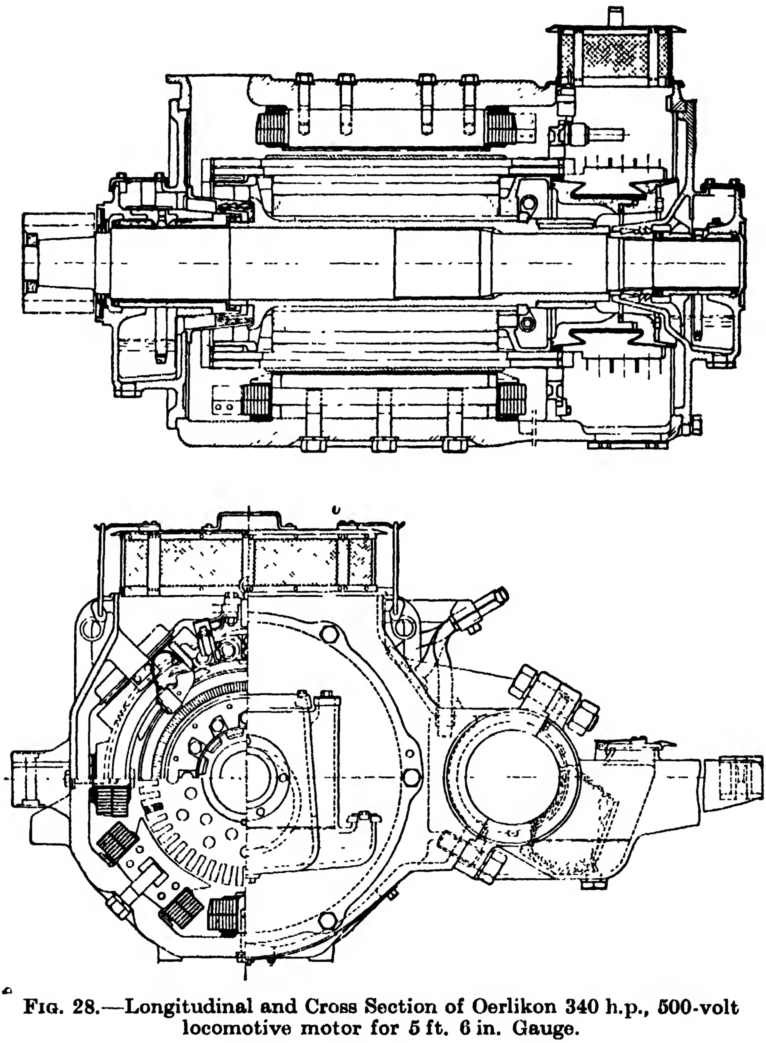


Fig. 28.—Longitudinal and Cross Section of Oerlikon 340 h.p., 500-volt locomotive motor for 5 ft. 6 in. Gauge.

"jack-shaft") carried in suitable bearings fitted to the locomotive frame, and driving the wheels from this shaft by cranks and horizontal connecting rods; (2) by fixing the gear-wheel to a quill (or hollow shaft) which surrounds the driving axle with suitable clearances and is centred in bearings in the motor frame, the quill being connected to the driving wheels by springs or a universal coupling through which the torque is

transmitted ; (3) by mounting the gear wheel in a suitable bearing outside the driving wheel and connecting these members together by a special linkwork (Brown-Boveri system). Further details are given in Chapter XVII, and at present we shall discuss the manner in which these methods of power transmission affect the motors.

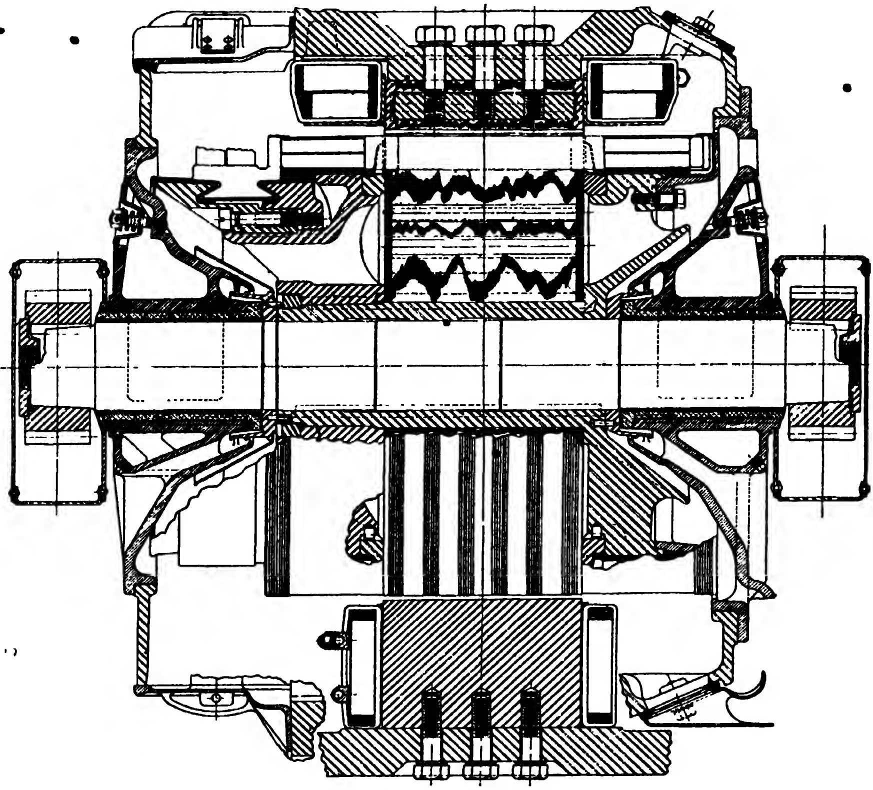


FIG. 29.—Longitudinal Section of 452-h.p., 1500-volt, Forced Ventilated Railway Motor (4 ft. 8½ in. Gauge). (General Electric Co., Schenectady.)

The **frame-mounted geared motor with connecting-rod drive** may be employed for slow-speed locomotives when the power equipment is to consist of one or two motors of moderately large output and a number of driving wheels are to be coupled together by coupling rods. The motor is, in some cases, arranged vertically above the jack shaft, the motor frame being of the open type and mounted on the locomotive framing at floor level. In other cases a pair of box-frame motors are mounted on each side of the jack shaft and their pinions mesh with a common gear wheel fixed to the jack shaft.

An example of a motor for the latter form of mounting is shown in Fig. 31. The motor is rated at 650 h.p., 1400 volts, 530 r.p.m., and is forced ventilated. Twin helical gearing is employed and springs are fitted in the pinions for the purpose of obtaining flexibility between the two sets of gearing, the gear wheels being solid. The motor frame is supported by transverse members of the locomotive frame, and, except for this feature, it closely resembles an ordinary box frame. It has four

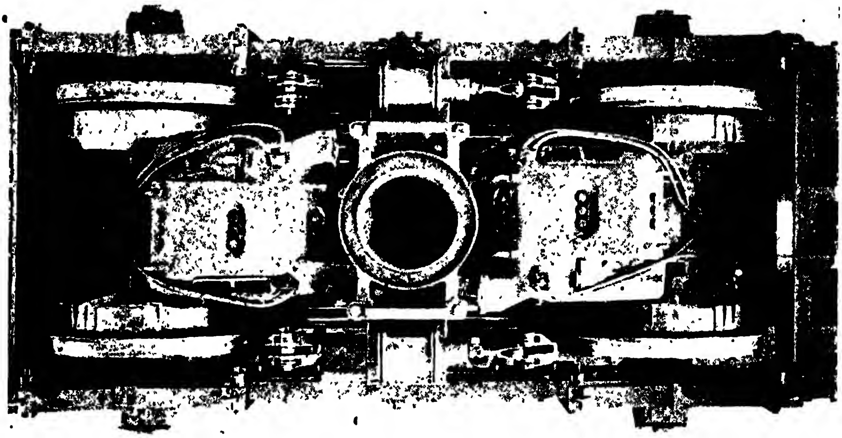


Fig. 30. View of Locomotive Truck, showing Motors in position. [Part equipment of Chicago, Milwaukee and St. Paul 260-ton locomotive built by General Electric Co.]

poles and the excitation winding is arranged in three sections, so that two steps of field control can be employed.

The armature has a four-circuit lap winding which is fitted with equalizing rings.

The characteristic curves of the motor are given in Fig. 32, and represent the performance of the motor through the gearing and side rods.

The **frame-mounted geared motor with quill drive** is now usually built as a twin motor, the two armatures being geared to common gear wheel. Fig. 33 shows the general arrangement and a view of a twin motor. This construction possesses a number of advantages over a single motor having the same output as the twin motor. Thus (1) only single, instead of twin, gearing is necessary, and therefore a greater proportion of the distance between the wheel hubs is available for the armature and commutator; (2) the armature and frame diameters of the twin motor are smaller than those of the single motor, and therefore a higher gear ratio and a higher armature speed may be adopted for the twin motor; (3) the armatures of the twin motor may be permanently connected in series, and such an arrangement enables a very satisfactory design of motor to be obtained for high-voltage circuits; (4) the smaller armatures with single gearing are easier and less costly to maintain than larger armatures with twin gearing.

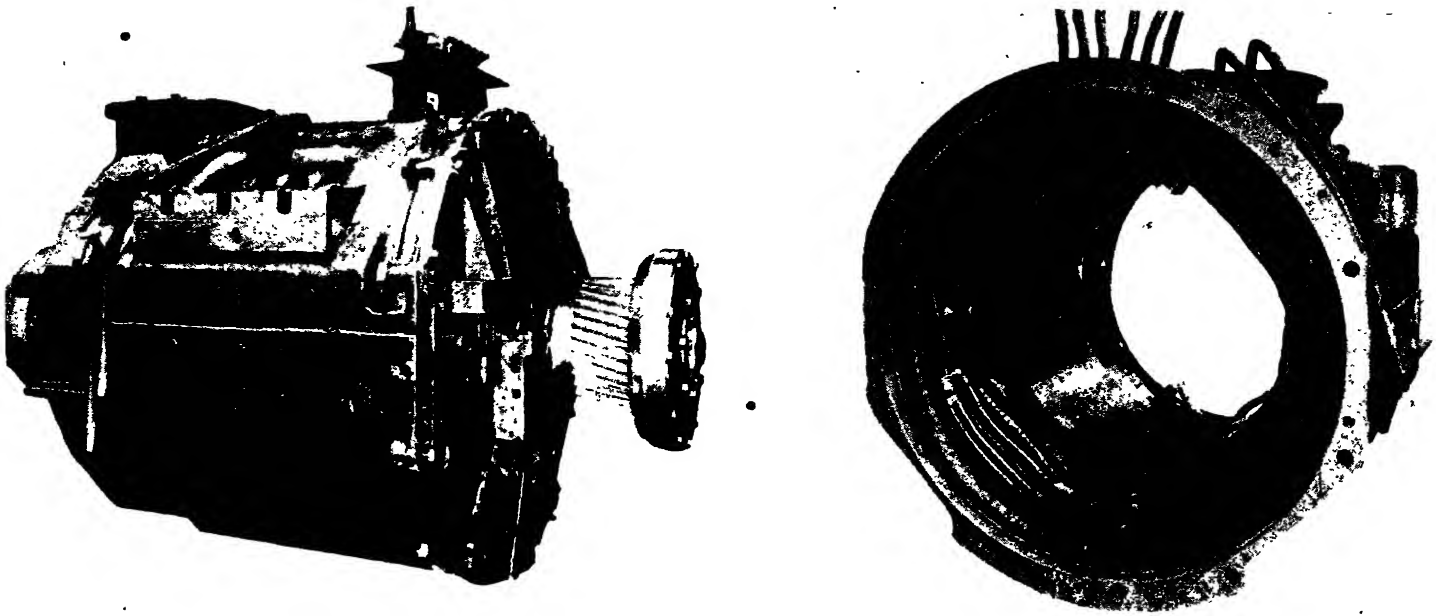


Fig. 31.—Metropolitan-Vickers 650 h.p. Frame-mounted Motor for Freight Locomotive.

The **frame-mounted geared motor with Brown-Boveri linkwork transmission** between gear-wheel and driving-wheel (described on p. 423) enables the whole width between the wheel flanges to be utilized for the motor. Hence for a given diameter of driving wheel a larger motor may be employed than would be possible with a geared quill drive. For example, with 69 in. (1750 mm.) driving wheels and 4 ft. 8½ in. gauge, a motor having a one-hour rating of 1000 h.p. (and a continuous rating of 825 h.p.) can be accommodated. Such motors have been built by Messrs. Brown-Boveri for the Paris-Orléans Railway. A motor is shown in Fig. 34, from which a number of interesting features may be

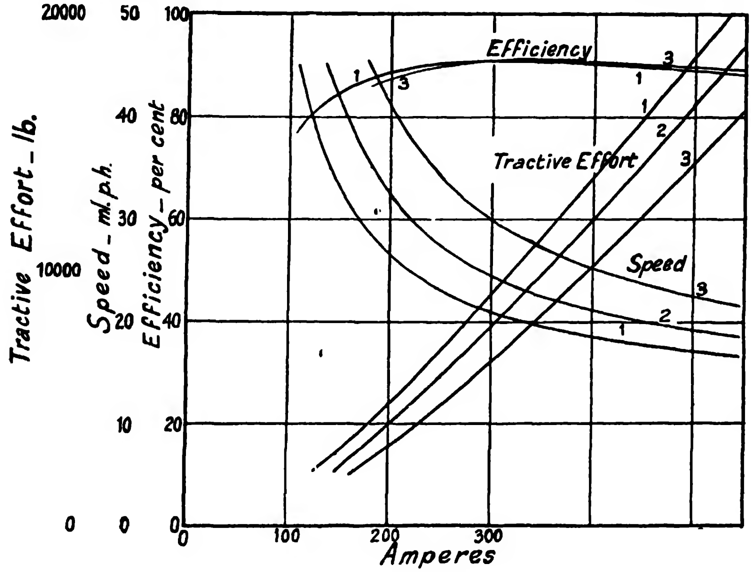
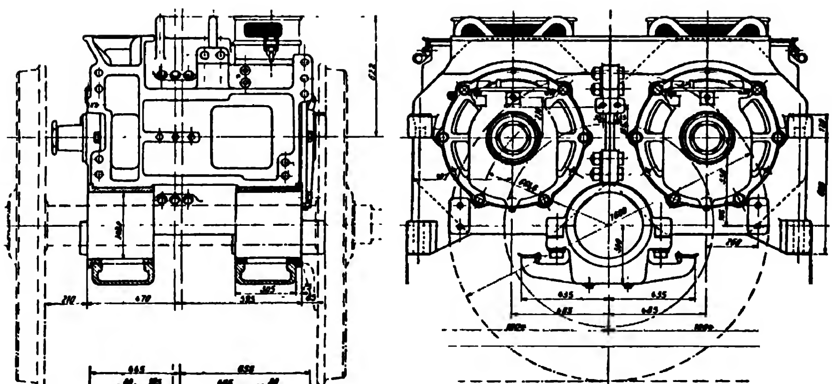


FIG. 32.—Characteristic Curves of Motor illustrated in Fig. 31 (675 h.p., 1400-volts, 400 amperes, 48 in. wheels, 4·15 : 1 gear ratio). Numbers attached to Curves indicate connection of Field Winding (e.g. 1, Full Field ; 2, Intermediate Tapped Field ; 3, Weak Tapped Field).

observed. Thus, the motor is a six-pole machine with commutating poles and six sets of brushes. Provision is made for inspecting and changing the brushes by arranging the brush-gear on a yoke ring, which, after the connections have been released, can be rotated by means of a worm and worm-wheel operated by a cranked handle. The armature bearings (which are of the babbited-sleeve type with self-oiling rings) are carried in cast steel end-shields, which are provided with feet (for mounting the motor on the frame of the locomotive) and ventilating ducts. A motor-driven blower is mounted directly above the air-duct opening in the back end-shield, the blower, when running, delivering about 4250 cub. ft. of air per minute at a pressure of about 4 in. water column. The back-end of the armature is fitted with a double fan for circulating the air on the parallel system. The air leaves through the air duct in the commutator end-shield, the inspection openings shown in Fig. 34 being normally closed with solid covers.



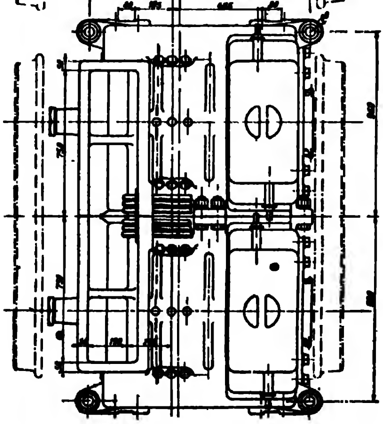


FIG. 33.—Interior View of Twin Motor Frame, and General Arrangement of Twin Motor with respect to Driving Axle (General Electric & Oerlikon Cos.).

The motor is designed for a combination of tapped- and shunted-field control, and typical characteristic curves are given in Fig. 35.

Gearless motors. When gearing is to be dispensed with two alternatives are possible, according to whether a number of motors of moderate output or one or two large motors are to be employed.

In the former case a special form of bipolar motor (developed by the General Electric Co., Schenectady) is adopted. The armature of this motor is mounted directly upon the axle, as shown in Fig. 36, and the field poles are built into the truck. The pole pieces and field coils are

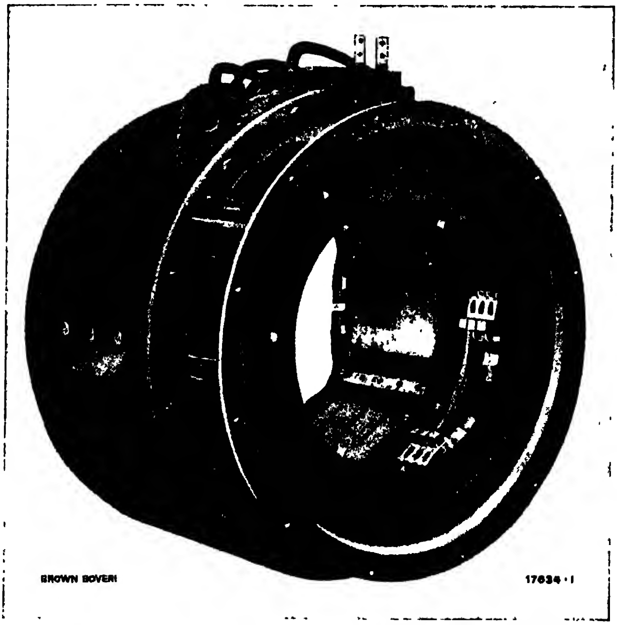


FIG. 34.—Brown-Boveri 1000 h.p. Frame-mounted Motor for High-speed Passenger Locomotive.

fixed to the cross transoms of the truck, and the magnetic flux passes horizontally in series through all the motors, the return path being provided by the side frames of the truck. The pole faces are almost flat, so as to allow vertical movements of the armature to take place relatively to the poles in consequence of irregularities in the track. The brush-holders are fixed to the transoms. The motor is enclosed by sheet-steel covers and is ventilated by a blower, the air entering at the commutator end and passing in parallel paths through the armature and over the surfaces of the armature and field coils. Owing to the wide neutral zone good commutation is obtained without commutating poles. Such motors have given very satisfactory service on the New York Central Railway locomotives—the maximum operating speed being of the order of 70 m.p.h.—and similar motors have been built for passenger locomotives

(having maximum operating speeds of 65 ml.p.h.) for service on the mountain divisions of the Chicago, Milwaukee, and St. Paul Railway.

When one or two large motors are to be employed the power must be transmitted to coupled driving wheels by cranks and connecting rods. The motors are relatively slow-speed machines having a large number of poles, and the mechanical design, with the exception of the bearings, resembles that of a stationary motor.

Speed control. When locomotives are required to operate mixed services a relatively large number of economical running speeds must

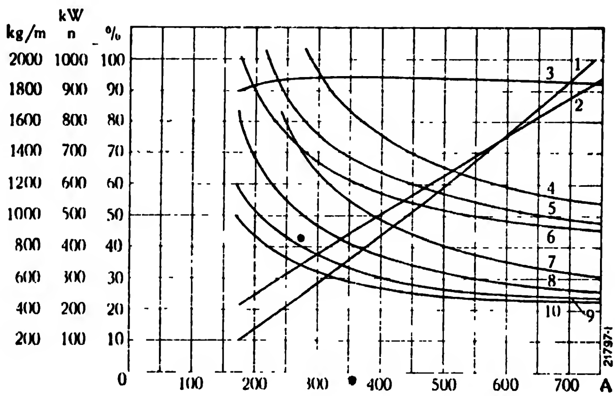


Fig. 35.—Characteristic Curves of Brown-Boveri, 1000 h.p., 1500-volt Locomotive Motor.

1. Torque in kgM.
2. Output in kW. (1350 V.)
3. Efficiency (per cent)
4. Armature speed (r.p.m.) at 1350 V., 61% excitation
5. ,, ,, ,, ,, 1350 V., 78% ,,
6. ,, ,, ,, ,, 1350 V., 100% ,,
7. ,, ,, ,, ,, 675 V., 43% ,,
8. ,, ,, ,, ,, 675 V., 61% ,,
9. ,, ,, ,, ,, 675 V., 78% ,,
10. ,, ,, ,, ,, 675 V., 100% ,,

be provided. These speeds may be obtained by a combination of voltage and field control; the former being obtained with multi-motor equipments by grouping the motors in series, series-parallel, and parallel, as explained in Chapter VIII, and the latter by tapped-field or shunted-field control.

With motors of large output sufficient space is available inside the motor to permit the main field winding to be divided into three sections, thereby giving three speeds corresponding to a given armature current and voltage. Additional speeds may be obtained by shunting the field winding.

An example of a motor in which five economical running speeds (for a given voltage and armature current) are available is shown in Figs. 34 and 37. This motor forms part of the four-motor equipment of one of the locomotives built by Messrs. Brown, Boveri for the Paris-Orléans Railway, and by the combination of double series-parallel and field control, fifteen economical operating speeds are available for the locomotive. As field control has been carried almost to the extreme limit in

this 1500-volt motor—the minimum exciting ampere-turns for a given armature current being 26 per cent of the full excitation at this current—

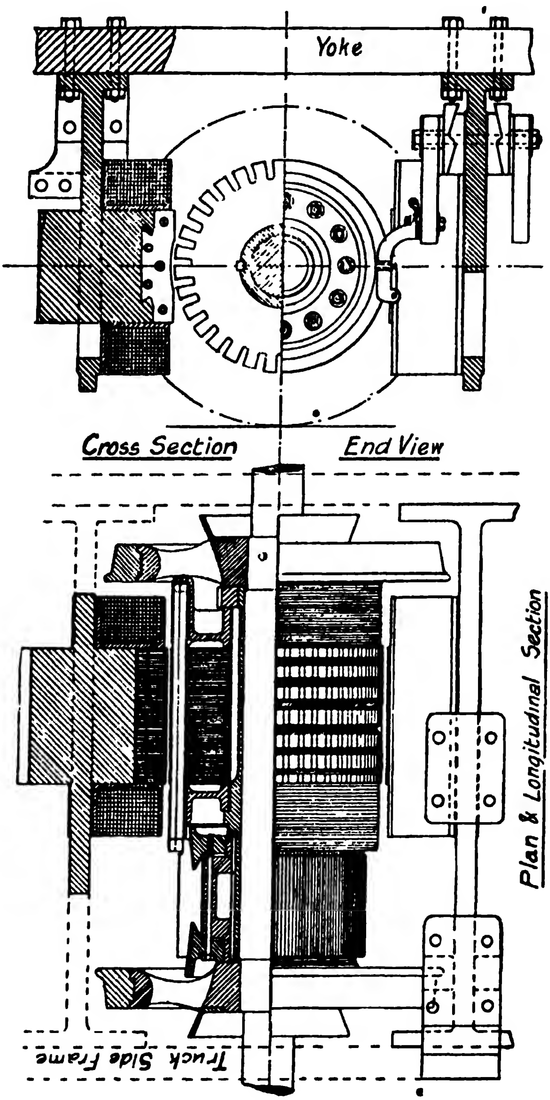


Fig. 36.—General Arrangement of 2-pole Gearless Motor (General Electric Co., Schenectady).

a pole-face or compensating winding (for neutralizing armature reaction) is provided to ensure stability and freedom from flashing when the motor is operating with weak fields, this provision being further necessary on account of the relatively large fluctuations in the operating voltage.

TROLLEY-BUS MOTORS

Motors for trolley-buses are similar in electrical design to tramway motors. In some of the earlier buses tramway motors were employed, but in all the latest buses a specially designed motor is employed, as in this manner the fullest advantage can be taken of the methods of power transmission and motor suspension which are peculiar to the trolley-bus motor. Accordingly, the trolley-bus motor possesses certain special mechanical features, of which the most important are—(1) the motor is rigidly

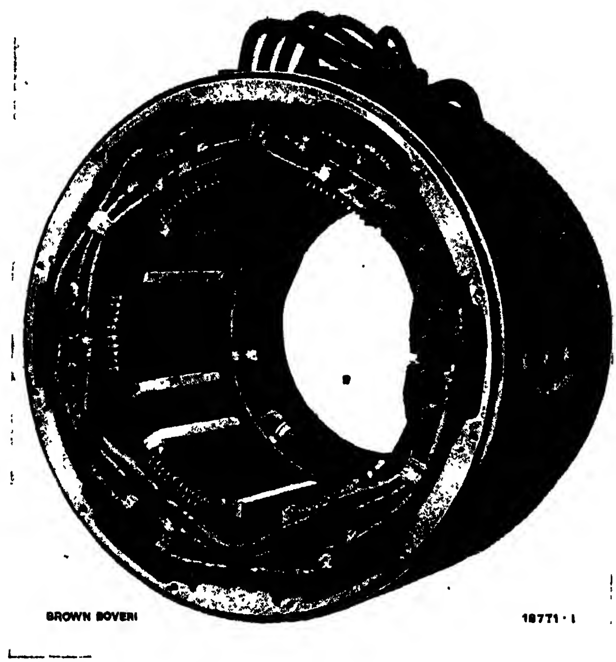


FIG. 37.—Frame of Brown-Boveri 1000 h.p. Locomotive Motor with Pole-face Winding.

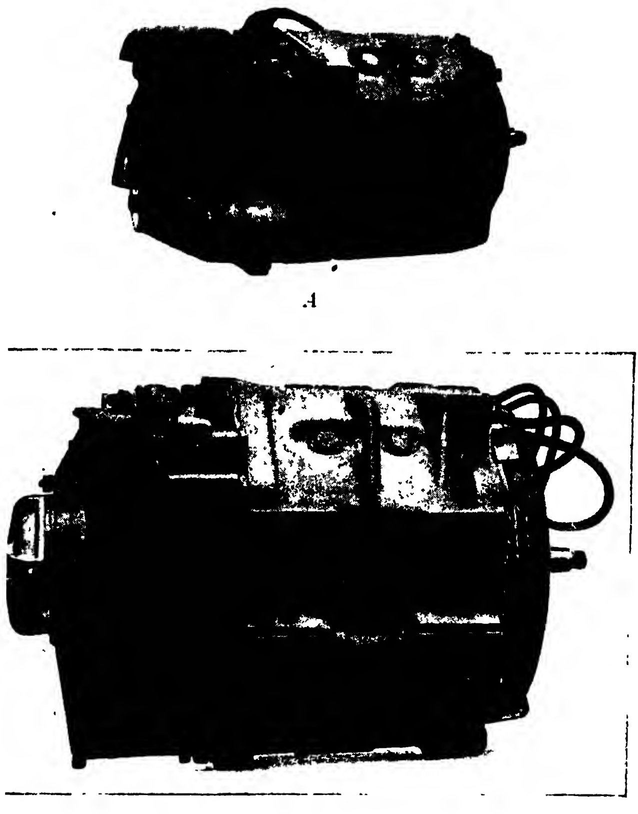
[NOTE—This motor has the exciting field winding divided into three sections, and five field strengths are obtainable for a given value of armature current.]

fixed to the chassis, which is spring supported from the road wheels; (2) the power is transmitted through a propeller shaft to a worm-driven differential gear in the back axle, this method of power transmission being similar to that adopted in internal-combustion-engined vehicles (except that, on the trolley-bus, there is no change-speed gearing).

On account of these features certain parts of the trolley-bus motor can be made lighter than the corresponding parts of a tramway motor. Thus the frame can be lightened, owing to its rigid support in the chassis and to the absence of axle bearings, while, owing to the general employment of roller bearings and the absence of gear-case supports, the frame heads can be made of aluminium alloy. Again, owing to the employment

of a worm-driven differential gear in the power transmission, the gear ratio is considerably higher than that obtaining in tramway practice, and in consequence the trolley-bus motor has a higher armature speed than the corresponding tramway motor, thereby enabling the former machine to be built lighter than the latter for the same power output.

The motors are four-pole machines with commutating poles; four sets of brushes are provided on the commutator, and ventilation is on the parallel system (p. 63). Owing to the relatively high armature



A

B

FIG. 38.—Motors for Trolley Omnibuses.
A, B.T.-H. Co.; *B*, English Electric Co.

speeds—which at the one-hour load are of the order of 1000 to 1100 r.p.m. —very efficient ventilation is obtained, and this, combined with the other mechanical features, has enabled the weight of the motor to be reduced to about 20 lb. per rated (one-hour) h.p. Typical motors are shown in Fig. 38.

Present-day practice with trolley-bus equipments employs a single motor having a one-hour rating of 50 or 60 h.p. The motor is fixed between the longitudinal members of the chassis, with the armature

shaft parallel to the longitudinal axis of the chassis. A flexible coupling is fixed to the armature shaft end, from which the propeller shaft is driven. Examples are given in Chapter XV.

Speed control. To provide two economical running speeds corresponding to those available on a tramcar, the single trolley-bus motor may be provided with two armature windings, commutators, and brush-gear; the two windings being identical and occupying the same slots in the armature core. The armature windings and commutators may be connected in series or parallel as desired, and two speeds, in the ratio of 1 : 2 approximately, may, therefore, be obtained for a given value of exciting current.

Alternatively, series-parallel control may be obtained by employing two smaller (25 to 30 h.p.) motors, which are mounted in tandem on the chassis. The single double-commutator motor, however, is the better proposition, as it is lighter, cheaper, more efficient, and occupies less longitudinal space in the chassis, than the two tandem-mounted motors.

When one single-commutator motor is employed, two economical speeds are obtained by shunted-field control, but in this case the ratio of speeds is between about 1 : 1·2 and 1 : 1·4.

APPENDIX TO CHAPTER IV

APPLICATION OF ROLLER BEARINGS TO TRACTION MOTORS

ROLLER armature bearings for tramway and trolley-bus motors are now favoured by many tramway engineers on account of the long life and low maintenance costs of these bearings when properly fitted and lubricated.

The **type of bearing** in general use with modern motors has short cylindrical rollers; the tapered (adjustable) roller type, although employed successfully in the automobile industry, being unsuitable for traction motors on account of difficulties due to the longitudinal expansion of the armature shaft being greater than that of the frame of the motor.

With the cylindrical roller type of bearing (which is non-adjustable) the hardened-steel rollers are mounted between two accurately finished races of hardened steel, the rollers being maintained in their correct relative positions by a gunmetal cage. End play of the rollers is limited by flanges formed on *one* of the races. The inner race is fixed to the armature shaft, and the outer race is securely clamped between caps in a seating in the frame-head of the motor. A definite location of the armature with respect to the frame is obtained by fitting a ball-bearing alongside the roller bearing at the commutator end (Fig. 38A), the ball bearing being so mounted that it cannot carry radial load. Hence any inequality in the expansions of armature shaft and frame is accommodated by a slight longitudinal movement of the rollers through the non-flanged race at the pinion end.

In the **design of mountings** for roller bearings careful attention is necessary to the maintenance of a good fit of both inner and outer races, and to the sealing of the bearing chambers against loss of lubricant and the ingress of water and dirt.

The inner race should be a press fit on the shaft, and the seating for the outer race should be bored as nearly as possible the exact diameter of the race.

The fit of the inner race after successive removals from the shaft can be preserved by mounting the race upon a sleeve which fits upon a taper formed on the shaft. Examples of this method of mounting, for the commutator and pinion ends, are shown in Fig. 38A. The sleeves are secured to the shaft by

locked nuts. They are drawn off the shaft when necessary by special tools which screw into special threads provided in the sleeves.

In some cases the inner race is mounted on a parallel sleeve which is shrunk on to the shaft and is secured by a locked nut. This sleeve can be readily renewed in the event of the press fit between the inner race and its seating being lost due to a removal of the race.

As it is undesirable to make a practice of removing the inner races when the armature is to be removed from a box-frame motor, the frame-heads and

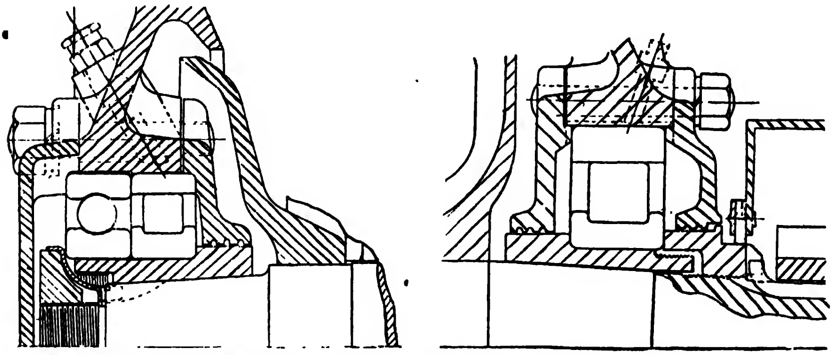


FIG. 38A.—Mounting of Roller Bearings in Traction Motors. (Metropolitan-Vickers.)

bearing caps should be so designed that the armature can be removed from the frame with the pinion-end frame-head intact, and with the bearing and inner end-cap remaining on the shaft at the commutator end.

The **seals** between the caps and the shaft are of the labyrinth type, so machined that an effective clearance of 0·005 in. radially is obtained. This type of seal effectively retains the lubricant. A thrower fitted to the shaft at the pinion end and outside the bearing will give protection against the ingress of water and dirty grease from the gear case.

Lubrication is effected by charging the bearings with pure mineral grease free from acid-forming constituents and "fillers." The grease is applied through a nipple from a "grease gun." It is of extreme importance that no grit be allowed to enter the bearing through the nipples.

The interval between successive service greasings depends upon local circumstances, and is of the order of about three months. Cases are on record where bearings have run 76,000 miles between successive greasings. Adequate lubricant in the bearings, however, is essential to their successful operation.

CHAPTER V

SINGLE-PHASE TRACTION MOTORS

The development of single-phase motors for electric traction has been confined almost exclusively to machines of the commutator type, as the single-phase induction motor is, inherently, incapable of exerting a large torque at starting. Moreover, the latter machine cannot readily be adapted for variable speeds, and, therefore, it is entirely unsuitable for traction service. On the other hand, the commutator type of motor can be designed to have a variable-speed characteristic similar to that possessed by a direct-current series motor, and can give a satisfactory performance at starting.

The **types of alternating-current commutator motors developed for electric traction** are those possessing a variable-speed (series) characteristic, and include the compensated (or neutralized) series motor, the compensated-repulsion motor, the brush-shifting repulsion motor (Déri type), and the series-repulsion or "doubly-fed" motor. All these motors are characterized by a laminated field structure (which, in the series motor, may have salient poles, but in motors of the repulsion type the polar face must be continuous) and an armature (or rotor) with a direct-current winding, commutator, and brushes. This type of rotor, with commutator and brushes, is essential for obtaining the variable-speed characteristic, and the introduction of these features into alternate-current machines is accompanied by operating conditions which are non-existent with induction motors. Expressed briefly, these new conditions involve the problems of power-factor and commutation, of which the latter is considerably more complicated than the commutation problem in direct-current machines. These problems and their solution will be discussed in detail in the pages which follow.

The present tendency in single-phase traction is towards the exclusive standardization of the series type of motor for low-frequency circuits purposes, but its speed control is simpler than that of other types of (16⅔ cycles), as this machine is not only more satisfactory for traction motors.

For 25-cycle circuits (which is the standard frequency for American single-phase electrification) the series-repulsion motor gives a better performance, and is of simpler construction, than the series motor. As, however, the present-day applications of this motor are not very great on account of the standardization of the lower frequency (16⅔ cycles) in European single-phase electrifications, and as its theory (which is treated extensively in the author's *Electric Motors and Control Systems*) involves the consideration of the theory of the repulsion motor (which is obsolete in so far as present-day single-phase traction is concerned), the series-repulsion motor will not be dealt with in the present volume.

The single-phase series motor has been adopted as standard for the extensive electrification of the Swiss Federal Railways and for other

extensive electrifications in Germany, Austria, Bavaria, Norway, and Sweden. For these reasons we shall consider only this type of motor.*

Theory of Single-Phase Series Motor

The simplest form of single-phase series motor consists of a laminated magnetic circuit and an armature, with commutator and brushes, which closely resembles the armature of a low-voltage direct-current motor. The main excitation is supplied by a field winding which is connected in series with the armature.

If such a motor is supplied at standstill with alternating current of low frequency a pulsating torque is developed, and the relationship between the mean value of the torque and the root-mean-square value of the current is almost identical with that obtained when the motor is supplied with direct current.

The similarity between the performance with direct and alternating current follows from the fundamental principles of electromagnetic commutator machines. Thus in any electromagnetic machine the magnitude of the torque developed at any instant is directly proportional to the product of the values, at that instant, of the flux and armature current, while the direction of the torque depends solely upon the relative directions, in space, of these quantities. With series excitation, an unsaturated magnetic circuit, and an alternating supply, the flux is practically in phase with, and is proportional in magnitude to, the armature current. Hence the torque at any instant is approximately proportional to the square of the current.

Relationship between torque and current. The relationship between the mean value of the torque and the root-mean-square (r.m.s.) value of the current is readily deduced for the simple case when both current and flux follow sine laws. Thus if the current is given by $i = I_m \sin \omega t$ and the flux by $\Phi = \Phi_m \sin \omega t$, the instantaneous torque $\mathfrak{T}_{inst}$, is

$$\begin{aligned}\mathfrak{T}_{inst} &= k\,\Phi\,i = k\,I_m\,\Phi_m \sin^2 \omega t\\ &= \tfrac{1}{2}\,k\,I_m\,\Phi_m(1 - \cos 2\omega t)\\ &= \tfrac{1}{2}\,k\,I_m\,\Phi_m - \tfrac{1}{2}\,k\,I_m\,\Phi_m \cos 2\omega t\end{aligned}$$

Thus the torque is pulsating, and may be resolved into a steady component (equal to $\frac{1}{2}\,k\,I_m\,\Phi_m$) and an alternating component (equal to $\frac{1}{2}\,k\,I_m\,\Phi_m \cos 2\omega t$) having a frequency double that of the supply current. The mean value of the latter, taken over a period of the supply current is zero.

Hence the mean torque over a period is

$$\begin{aligned}\mathfrak{T}_{mean} &= \tfrac{1}{2}\,k\,I_m\,\Phi_m\\ &= k\,I(\Phi_m/\sqrt{2})\end{aligned}$$

where $I(= I_m/\sqrt{2})$ and $\Phi_m/\sqrt{2}$ are the r.m.s. values of current and flux, respectively.

In the case of a purely unsaturated magnetic circuit the flux is directly proportional to the current, and the mean torque is

$$\mathfrak{T}_{mean} = k'I^2$$

* The theory of the repulsion, Déri, and series repulsion traction motors, together with constructional details and characteristic curves is given in the author's *Electric Motors and Control Systems* (Pitman).

The **function of the commutator** is the same in both single-phase and direct-current motors, viz. to enable each motor to exert a continuous torque. Thus with alternating-current operation the flux and armature current both alternate at the same frequency, and the torque exerted by any particular armature conductor when under a given pole face is always in the same direction. When this conductor moves to a position under a pole face of opposite polarity, the direction of the current in it is reversed (due to the action of the commutator and bushes), and the torque is in the same direction as before. Therefore the commutator

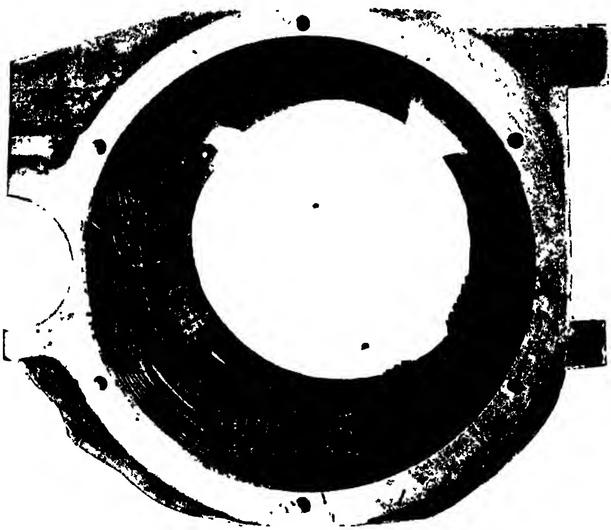


FIG. 39.—Partially Wound Stator of Westinghouse Single-phase Series Motor, showing compensating winding in position.

performs the same functions whether the supply is direct or alternating, and is as necessary for one case as for the other.

Electrical conditions at starting. Two important conditions occur at starting, viz. (1) the power factor is extremely low, (2) the armature coils which are short-circuited by the brushes on the commutator will probably become overheated and vicious sparking will occur if the segments connected to these coils break contact with the brushes (due to any slight movement of the armature).

The low power factor is due to the inductances of the armature and field windings. The inductance of the former is due to the magneto-motive force produced by the current in the armature, the direction of this magneto-motive force being along the neutral, or brush, axis. Since this magneto-motive force is not essential for the production of torque in the motor it may be neutralized without affecting the relationship between torque and current.

In order to neutralize the magneto-motive force of the armature a stationary winding, producing an equal, but opposing, magneto-motive force, must be placed as closely as possible to the armature winding, and must be distributed in space in the same manner as the armature winding. Such a winding—called a neutralizing or **compensating winding**—is, therefore, always provided in commercial motors and is located in the pole faces, as shown in Fig. 39: it may be connected in series with the armature winding (i.e. conductively excited), or, alternatively, it may be short-circuited upon itself (i.e. inductively excited). In the latter case the neutralizing ampere-turns are derived by transformer action from the armature winding, but, due to inevitable losses and to the presence of an air gap between the two windings, the neutralizing ampere-turns so obtained will always be lower than the armature turns, and, therefore, a portion of the armature magneto-motive force will remain unneutralized. The method, however, possesses the advantage that the number of turns in the winding do not require to be so carefully chosen as for the conductively-excited winding. But with present-day motors the conductively-excited winding is preferred on account of the better performance of the motor.

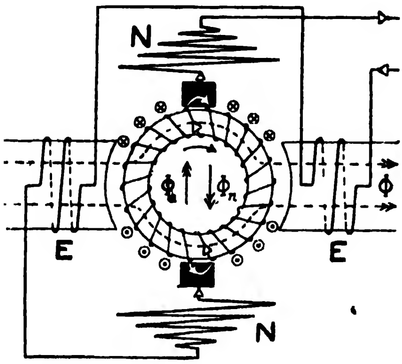


FIG. 40.—Diagram showing directions of Transformer-E.M.F.s and Circulating Currents in Armature of Single-phase Series Motor. NOTE—Φ_a, Φ_n denote, respectively, the fluxes which would be produced by the separate action of armature and compensating windings.

The overheating of certain armature coils and the vicious sparking at the brushes are due to the relatively large circulating currents which are induced by the alternating main flux in the coils short-circuited by the brushes, these coils and the main field coils acting as the secondary and primary windings of a transformer. The conditions are represented in Fig. 40, which shows the relative directions, at a given instant, of the currents and fluxes for a ring armature winding with the brushes in the neutral position. It will be observed that the armature coils occupying the neutral zones are traversed by the whole of the main flux, and, therefore, the coils which are short-circuited by the brushes will be the seat of relatively large circulating currents. The steps which must be taken to reduce these currents in commercial motors are considered in the discussion of commutation which is given later.

Electrical conditions when running. These involve the consideration of (1) the relationship between speed and torque, (2) power factor, (3) commutation.

The relationship between speed and torque is best obtained by deriving first the relationships between (1) torque and current, (2) speed and current. The relationship between torque and current has already been obtained, and the relationship between speed and current is readily

obtained from the fundamental principles governing the action of electro-magnetic machines. Thus, in any rotating armature supplied with energy through brushes and commutator, the E.M.F. generated in the armature winding due to its rotation—this E.M.F. will be called the **dynamic E.M.F.**—together with any other internal E.M.F.s due to the current and the main flux must, at every instant, balance the external E.M.F. applied to the brushes.

With a direct-current supply only two internal E.M.F.s have to be considered, viz. (1) the dynamic E.M.F. (usually called the "back-E.M.F." or "counter-E.M.F." in direct-current motors), and (2) the voltage drop due to the resistance of the armature circuit. But with an alternating-current supply other E.M.F.s are present, which are due to (3) the alternations of the main flux through the armature winding, and (4) the alternations of the current in the armature conductors. The former are called **static E.M.F.s** and the latter **inductive E.M.F.s**.

The static E.M.F.s due to the alternations of the main flux through those armature coils which form the electrical circuits between the brushes cancel out when the magnetic circuits are symmetrical (i.e. when the flux from each pole divides equally in passing through the armature core, as indicated in Fig. 40) and the axis of the brushes is perpendicular to the axis of the main flux, these conditions being represented diagrammatically in Fig. 40. But in those coils which are short-circuited by the brushes the E.M.Fs. induced by the main flux are active and set up circulating currents in the closed circuits.

The inductive E.M.Fs. due to the alternations of the current in those armature coils which form the circuits between the brushes are almost negligible in commercial motors which are provided with pole-face windings for neutralizing the magneto-motive force of the armature.

The dynamic E.M.F. is, therefore, the principal internal E.M.F. in the armature circuit (i.e. that portion of the armature winding between the brushes) of a commercial single-phase motor when the armature is rotating.

The r.m.s. value of this E.M.F. is given by the equation

$$E = (2/\sqrt{2})\, p\, \Phi_m N n \times 10^{-8} \quad . \quad . \quad . \quad . \quad . \quad (15)$$

where p denotes the number of poles, N the number of turns per circuit of the armature winding, n the speed in revolutions per second, and Φ_m the maximum or crest value of the flux per pole, which is assumed to vary sinusoidally with respect to time.

Hence the speed in revolutions per second is given by

$$n = E \times 10^{8}/[(2/\sqrt{2})p\Phi_m N]$$

which is of similar form to the speed equation for a direct-current motor.

The r.m.s. value of the static E.M.F. induced in the exciting winding by the alternations of the main flux is

$$E_s = (2\pi/\sqrt{2})\, f\, N_f\, \Phi_m \times 10^{-8} \quad . \quad . \quad . \quad . \quad . \quad (16)$$

where f denotes the frequency of the supply current, N_f the number of turns in the exciting winding, and Φ_m has the same significance as in equation (15).

Power factor. The conditions under which a high power factor may be obtained can be determined by a consideration of the vector diagram for the motor. For the simplest case of a motor in which the armature reaction is neutralized, and only resistance losses in the armature and field circuits are present, the vector diagram is shown in Fig. 41. In this diagram the flux is represented by OY and is the vector of reference, the current—which is in phase with the flux—by OI, and the terminal voltage—which leads the current by the angle ϕ—by OV. The terminal voltage balances the vector sum, Oc, of the internal E.M.F.s, of which the dynamic E.M.F. is represented by Oa, the voltage drop due to the total resistance of the motor by ab, and the inductive E.M.F. induced in the field (excitation) winding by bc.

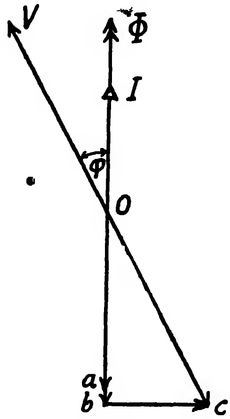


FIG. 41.

Hence for a high power factor (i.e. for ϕ to be a small angle) the inductive E.M.F. must be small in comparison with the dynamic E.M.F.

When, however, the resistance losses are ignored, a simple expression can be obtained for the power factor of the motor. Thus

$$\text{Power factor} = \cos\phi = \sqrt{\frac{1}{1 + [\frac{1}{2}\pi(n_s/n)\,(N_f/N)]^2}} \tag{17}$$

This expression is obtained as follows

$$\tan\phi = \frac{\text{inductive E.M.F.}}{\text{dynamic E.M.F.}} = \frac{(2\pi/\sqrt{2})\,f\,N_f\,\Phi_m \times 10^{-8}}{(2/\sqrt{2})\,p\,n\,N\,\Phi_m \times 10^{-8}}$$

$$= \frac{\pi}{2}\cdot\frac{n_s}{n}\cdot\frac{N_f}{N}$$

$$\cos\phi = (1 + \tan^2\phi)^{-\frac{1}{2}} = \{1 + [\tfrac{1}{2}\pi(n_s/n)\,(N_f/N)]^2\}^{-\frac{1}{2}}$$

where n_s is the synchronous speed ($= f/\frac{1}{2}p$ rev. per sec.), f the frequency of supply, p the number of poles, n the speed of rotation of the armature, N_f the *total* number of turns in the exciting winding, N the number of turns per circuit of the armature (i.e. the number of turns in series between the brushes), Φ_m the crest value of the flux per pole, the distribution of which is assumed to be sinusoidal.

Hence for a given motor the power factor at the highest speed (i.e. at light load) will approach unity and will decrease as the speed decreases.

Design factors affected by power factor considerations. For a given voltage and load the power factor will be higher the lower the value of the product $(n_s/n)\,(N_f/N)$. Since the speed of rotation at normal load is governed by considerations of the permissible peripheral speed at light load, the former can be considered to have a definite limiting value, and, therefore, with the speed of rotation (n) fixed, a low value for (n_s/n) necessitates a low synchronous speed, which condition requires (1) a low frequency of supply, (2) a relatively large number of poles.

Also a small number of turns in the exciting winding necessitates a magnetic circuit of low reluctance, i.e. low flux densities and a small air gap. Moreover, the combination of low flux densities and a relatively large number of poles results in a relatively low flux per pole.

On account of the unsaturated magnetic circuit the speed-current curve of the motor is considerably steeper at the rated load of the motor than that of the direct-current series motor.

Hence the commercial single-phase series motor must be supplied at low frequency and must have—

(1) A pole-face winding for neutralizing the armature magnetomotive force.

(2) A relatively large number of poles.

(3) A low flux per pole.

(4) A magnetic circuit worked at low flux densities.

(5) A small air gap.

With such a motor the full-load speed is usually about three to four times the synchronous speed, and the number of turns in the field winding is about one-third the number of armature turns per circuit. Hence, theoretically, the power factor at full load—as given by equation (17)—is

$$\cos\phi = [1 \times (\tfrac{1}{2}\pi \times \tfrac{1}{3} \times \tfrac{1}{3})^2]^{-\frac{1}{2}} = 0{\cdot}985,$$

but in practice—owing to the leakage reactances of the field winding and armature (which were ignored in deriving equation (17))—the power factor would be about 0·95.

Since the torque is proportional to the product of total flux and armature ampere-turns, the armature should carry as many ampere-turns as possible, and as armature-reaction effects are negligible, the electric loading (i.e. the ampere-turns) can be pushed to the extreme limit (which is governed solely by considerations of heating).

Hence in the single-phase motor, the large number of armature ampere-turns, the low flux densities and the small air gap, result in the ratio [field (excitation) ampere-turns per pole/armature ampere-turns per pole] being less than unity, whereas in a direct-current traction motor this ratio is greater than unity. Relative values, for rated load, are—

Single-phase motors	0·25–0·5
Direct-current motors without commutating poles	2–3
Direct-current motors with commutating poles .	1·5–2

Thus, considerations of power factor require the single-phase series motor to be designed on radically different lines to the direct-current series motor in respect to armature and field ampere-turns and flux densities.

Commutation. The commutating conditions in the simple series motor are considerably more complicated than those in a direct-current motor, as, in addition to the E.M.Fs. induced in the commutated coils by the reversal of the armature current, there is a static E.M.F.—called the "transformer E.M.F."—which is induced in these coils by the alternations of the main flux. The presence of the latter E.M.F. and the circulating currents produced by it have already been referred to in connection with the electrical conditions at starting. Now we shall discuss the manner it affects the performance of the motor when running.

Effects caused by circulating currents. Since the magnitude of the transformer E.M.F. in a given motor is proportional to the main flux its largest values occur at heavy loads (i.e. at high current inputs), so that under these conditions severe sparking is liable to occur, as the coils undergoing commutation have the circulating currents due to the transformer E.M.F. superimposed upon the current which is being commutated.

The circulating currents, however, produce other effects which are detrimental to the performance of the motor. Thus, since the coils occupying the neutral zone are in the position of maximum mutual inductance with respect to the exciting winding, and the circulating currents are produced by induction, the ampere-turns set up by the short-circuited coils act in opposition to the ampere-turns producing the main flux (see Fig. 40). This reaction results in a weakening of the main flux as well as a phase displacement between this flux and the armature current, thereby reducing the torque. These effects are shown in the vector diagram of Fig. 42, in which OY represents the main flux, OB the ampere-turns producing this flux, and OF the transformer E.M.F. (which is in time quadrature with the flux). If we disregard any other E.M.F.s that may be induced in these coils, then the circulating currents produced by the transformer E.M.F. can be represented by OG, in phase with OF. The reaction ampere-turns, due to the circulating currents, are represented by OC, and act along the axis of the field winding. Therefore, OB represents the resultant of the field ampere-turns and the reaction ampere-turns. Hence the field ampere-turns are represented by OA, and the main current by OI, which leads the flux by the angle θ, thereby reducing the angle ϕ (Fig. 41) and improving the power-factor.

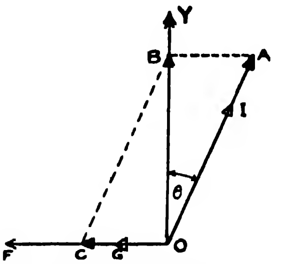


FIG. 42.—Effects due to Circulating Currents.

The improvement in the power-factor, however, is accompanied by a reduction in the torque, since the latter is represented by the product $OY \times OI \cos\theta$.

Therefore the circulating currents are not only detrimental to commutation, but they affect adversely the output and efficiency. They also lead to increased losses and heating, and necessitate more ampere-turns to be supplied by the main field winding than are required for magnetic purposes.

Methods of reducing circulating currents. The circulating currents may be eliminated when the armature is rotating by neutralizing the transformer E.M.F. To effect this result a dynamic E.M.F. (called the "commutating E.M.F.") must be generated in the coils in which the transformer E.M.F. is induced. This is obtained by providing in the neutral zone a commutating flux of the correct flux density having a time phase-difference of 90° with respect to the main flux, since the transformer E.M.F. has a phase-difference of 90° (lagging) with respect to the main flux. The commutating poles would, therefore, require shunt excitation, as a series winding would produce a commutating flux in phase with the main flux.

If complete neutralization of the transformer E.M.F. is to be obtained over a range of speeds the magnitude of the commutating flux must be proportional to the quotient (main flux/speed). This condition follows from the fact that the magnitude of the transformer E.M.F. is proportional to the main flux, and the commutating E.M.F. is proportional to the product of armature speed and commutating flux. But the speed is approximately proportional to the quotient (terminal voltage/main flux). Hence, the commutating flux would have to be proportional to the quotient [(main flux)^2/terminal voltage], a condition which would be difficult to satisfy in practice.

In a commercial motor it is only practicable to neutralize the transformer E.M.F. over a limited range of loads. But, what is of greater importance, this voltage cannot be neutralized to the slightest degree at starting.

The magnitude of the circulating currents at starting can be reduced by (1) reducing the magnitude of the transformer E.M.F., (2) increasing the resistance of the path of the circulating currents.

Since the static E.M.F. (E_s) induced in a coil of N_c turns by the alternations of a flux Φ_m is given by

$$E_s = (2\pi/\sqrt{2})N_c f \Phi_m \times 10^{-8},$$

therefore, if m coils are short-circuited by a brush, the transformer voltage (E_t) causing circulating currents in these coils will be given by

$$E_t = (2\pi/\sqrt{2})m\, N_c f \Phi_m \times 10^{-8}$$

Hence E_t can be reduced by (*a*) reducing the number of coils short-circuited by a brush, (*b*) reducing the number of turns per armature coil to the minimum value (viz. unity), (*c*) adopting a low flux and a low frequency. Observe that a low frequency and a low flux per pole are also necessary from considerations of power factor.

The resistance of the path of the circulating currents may be increased by (*d*) the use of high-resistance brushes, and (*e*) the introduction of "resistance leads" or high-resistance connections between the armature coils and the commutator segments.

The number of coils short-circuited by a brush can be reduced to a minimum by the use of narrow brushes covering not more than two segments. These brushes are generally of high resistance so as to conform to condition (*d*). Alternatively, a duplex armature winding—which consists of two re-entrant windings connected to a single commutator, the commutator segments being connected alternately to the coils of each winding—may be employed. But this complication is unnecessary when a low frequency is adopted.

The reduction of the armature turns per coil to unity introduces a limitation to the armature voltage, since, with a multiple-circuit armature winding and a large number of poles, the number of segments per pole (and therefore the turns per circuit and the voltage) are limited by the largest permissible diameter of commutator and the narrowest width of segment. The minimum width of segment, however, must be chosen with reference to the minimum practicable thickness of the brushes in order that condition (*a*) may be satisfied.

The **resistance connections** consist of a high-resistance alloy (constantan, "Eureka," rheostan), and connect the junctions of the armature

coils to the commutator segments in the manner indicated in Fig. 43. These connections are located either in the bottom of the slots with the armature winding, as described on p. 102, or between the front armature connections and the commutator segments, as shown in Fig. 66 (p. 114).

Other E.M.F.s affecting commutation. In addition to the transformer E.M.F. the coils undergoing commutation have induced in them an inductive voltage (called the "reactance voltage of commutation") due to the reversal, or commutation, of the armature current, while in machines not fitted with commutating poles there is usually present another E.M.F. (called the "rotation voltage of commutation") which is produced by the armature conductors cutting any residual cross flux

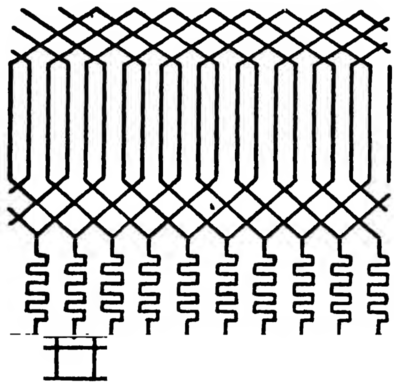


FIG. 43.—Diagram showing Resistance Connections between Armature Winding and Commutator.

in the neutral zone (due to incomplete neutralization of the armature magneto-motive force).

The reactance voltage may be estimated by means of formulae* derived for direct-current machines, provided that the differences in armature construction and operation are taken into account. For example, (1) the slots in a single-phase armature are usually of the partially-closed type, and (2) the instantaneous value of the armature current at the commencement of commutation may differ from that at the end of commutation.

The reactance voltage is approximately in phase with the armature current, and its magnitude depends upon the current, the speed, and other factors concerned with the design of the motor.

The rotation voltage of commutation, when present, is in phase with the cross flux, and the latter is in phase with the armature current. It is usually of small magnitude in comparison with the transformer E.M.F. and the reactance voltage, and is calculated from the product of cross-flux, speed, turns per coil, and number of coils short-circuited

* See *The Dynamo* (Hawkins), vol. I; *Single-Phase Commutator Motors* (Punga); "A Theory of Commutation," by Lamme (*Transactions of American Institute of Electrical Engineers*, vol. 30, p. 2359). Punga's treatise also discusses the modifications to be applied to reactance voltage formulae when used for single-phase motors.

by a brush. For a given motor it is proportional to the product of current and speed.

The reactance and rotation voltages are, therefore, out of phase with the transformer E.M.F.; hence the vector sum of these voltages must be taken when calculating the resultant voltage (to which the resultant circulating currents are due) in the coils undergoing commutation.

Commutating poles. In view of the presence of the transformer E.M.F. and the reactance voltage, both of which reach their highest values at the heaviest loads, good commutation under these conditions is only possible when commutating poles are provided. Since these poles result in a considerable reduction in the magnitude of the circulating currents they lead to increased efficiency and lower losses, so that for given heating conditions a greater output can be obtained from a given armature core.

Usually the commutating pole takes the form of a special tooth having different proportions to the other teeth forming the pole face.

The ampere-turns to be supplied by the commutating pole must balance any unneutralized armature ampere-turns and provide the requisite magneto-motive force for passing the commutating flux through the pole, air gap, and armature teeth.

The magnitude of the flux density at the face of the commutating pole is determined from considerations of the peripheral speed of the armature, the resultant E.M.F. which is permissible in the coils undergoing commutation, and the magnitudes of the transformer E.M.F. and reactance voltage. When the resultant E.M.F. is zero (i.e. when complete neutralization of the transformer E.M.F. and reactance voltage occurs) the commutation is perfect and there are no circulating currents. To obtain this result the commutating flux must (1) be of such magnitude that the commutating E.M.F. balances the vector sum of the transformer E.M.F. and the reactance voltage, and (2) be in phase with the vector sum of these E.M.F.s.

Excitation of commutating poles. A number of methods of exciting the commutating poles in order to obtain the correct phase difference (which may be between 30° and 50°) between the main flux and the commutating flux have been developed,* but the simplest and most satisfactory method for low frequency motors consists of a plain series winding shunted with a non-inductive, or partially inductive, resistance. This method is now adopted by the principal Continental manufacturers of single-phase traction motors. The circuit diagram is shown in Fig. 44 and the vector diagram in Fig. 45.

In the vector diagram (which represents the conditions for ideal commutation) the magnitude and phase of the ampere-turns required to produce the commutating flux OZ is represented by Oq, while OY represents the main flux and OI the main current. If the armature ampere-turns are completely compensated, then the ampere-turns on the commutating pole must be equal to Oq. The current in the commutating-pole winding must be in phase with Oq; and if OH represents the current required, then OK—the vector difference of OI and OH—represents the current in the shunt resistance.

* See *Electric Motors and Control Systems*, pp. 67–71.

The voltage drop Ou in the commutating-pole circuit is obtained by compounding Ov (which represents the E.M.F. induced in the commutating-pole winding) with vu (which represents the internal voltage drop due to the resistance of the winding). The value of the shunt resistance is then obtained by dividing Ou by the shunt current OK.

The results obtained by this method of excitation have been quite satisfactory, and, with high-speed $16\frac{2}{3}$-cycle motors, the losses in the shunt resistance are only of the order of $\frac{1}{4}$ to $\frac{1}{3}$ of 1 per cent* of the output of the motor. With low-speed 25-cycle motors, however, the loss in the shunt resistance would generally be of such a magnitude to render this system of excitation impracticable.

Conditions limiting output. An important feature which affects the design of the single-phase series motor is that the output per pole

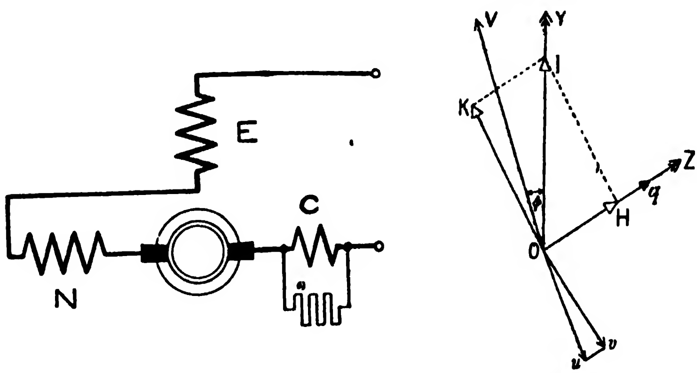


FIG. 44. FIG. 45.
Circuit and Vector Diagrams for Shunted Commutating-pole Winding.

obtainable from such a motor has a definite limiting value, as the following consideration will show. Thus if friction, windage, core losses, and magnetic reactions are ignored, the output of the motor is given by the product of the dynamic E.M.F. generated in the armature by its rotation in the main flux and the current input to the armature. But from equation (15) (p. 87) the dynamic E.M.F. is given by

$$E = (2/\sqrt{2})\, p\, \Phi_m N n \times 10^{-8}$$

where p denotes the number of poles, Φ_m the flux per pole, N the number of turns per armature circuit, and n the speed in revolutions per second. Hence the output (P) is given by

$$P = EI = p\, \Phi_m N I n \times (2/\sqrt{2}) \times 10^{-8}$$

or

$$P/p = \Phi_m N I n \times (2/\sqrt{2}) \times 10^{-8}$$

* See a paper on "Single-phase Traction," by Marius Latour (*Journal of the Institution of Electrical Engineers*, vol. 51, p. 518). An investigation of the losses with the above method of excitation is given in the paper (pp. 514–518).

See also a paper on "Commutation in Alternating-current Machinery," by the same author (*Transactions of American Institute of Electrical Engineers*, vol. 37, p. 355).

Now NI is equal to the total armature ampere-turns, and may be expressed in terms of the armature diameter (D) and the specific electric loading (Q)—i.e. ampere-turns per unit length (cm. or in.) of armature periphery—thus $NI = \pi DQ$. Also Φ_m can be expressed in terms of the transformer E.M.F., frequency, and other constants of the armature, as shown on p. 91. Effecting these substitutions, we have

$$\frac{P}{p} = \left(\frac{\sqrt{2}}{2\pi} \cdot \frac{E_t}{fmN_c \times 10^{-8}}\right) \pi DQ\, n \quad \frac{2}{\sqrt{2}} \times 10^{-}$$

When the number of turns per armature coil (N_c) is unity and the brush thickness is not greater than the width of two commutator segments (i.e. $m = 2$) this expression reduces to

$$P/p = \tfrac{1}{2}E_t\, DQ\, n/f$$

But if v denotes the peripheral speed of the armature in feet per minute, $v = 60\, n\, \pi D/12$, when the diameter of the armature is expressed in inches, so that $nD = v/5\pi$. Hence the output equation becomes

$$P/p = vQE_t/31{\cdot}4f \qquad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

Now Q and v have definite limiting values, the former being governed by considerations of heating and the latter by mechanical considerations.* Hence, with limiting values for v and Q, the output per pole is directly proportional to the transformer E.M.F. and inversely proportional to the frequency. Thus the transformer E.M.F. and frequency are very important features in the design of the motor.

The permissible value of E_t is governed by the magnitude of the circulating currents allowable under starting conditions. For a given frequency the output is, therefore, restricted by the transformer E.M.F. Hence any features—such as resistance connections and, in certain cases, starting the motor with reduced flux—which will lead to an increase in the permissible value of this quantity will result in an increased output, provided that the heating limit is not thereby affected.

The importance of a low frequency is again emphasized by equation (18). The adoption of a specially-low frequency—such as $16\frac{2}{3}$ cycles—instead of 25 cycles, therefore, results in improved power factor, higher efficiency, improved commutation, better starting performance, and fewer poles for a given output. These advantages have been recognized fully by Continental manufacturers of single-phase traction equipment, and the standardization of a frequency of $16\frac{2}{3}$† cycles, instead of 25 cycles, for single-phase railways on the Continent is the principal reason why single-phase traction has made such progress there.

General vector diagram for the ideal series motor. The compensated series motor, considered without losses, circulating currents, or other

* The peripheral speed at rated load may be of the order of from 5000 to 6000 ft. per minute, the limiting peripheral speed at light loads being of the order of 10,000 ft. per minute. The limiting value of Q for forced ventilation and the standard temperature rise permissible in railway motors is of the order of 500 ampere-turns per inch of armature periphery.

† The frequency of $16\frac{2}{3}$ cycles has been chosen in order to give a convenient ratio for the number of poles in frequency changers (which must be employed in the substations when the traction supply is taken from an industrial supply system of standard frequency, viz., 50 cycles).

defects, lends itself to a simple treatment in so far as the general vector diagram and predetermination of performance are concerned. The general vector diagram is readily obtained from the vector diagram of Fig. 41 (which refers to given operating conditions), as, if the terminal voltage is constant and the current input is varied, the voltage vectors (i.e. the vectors representing the dynamic E.M.F., the inductive E.M.F., and the reversed terminal voltage) always form a right-angled triangle of which the hypotenuse is of constant length.

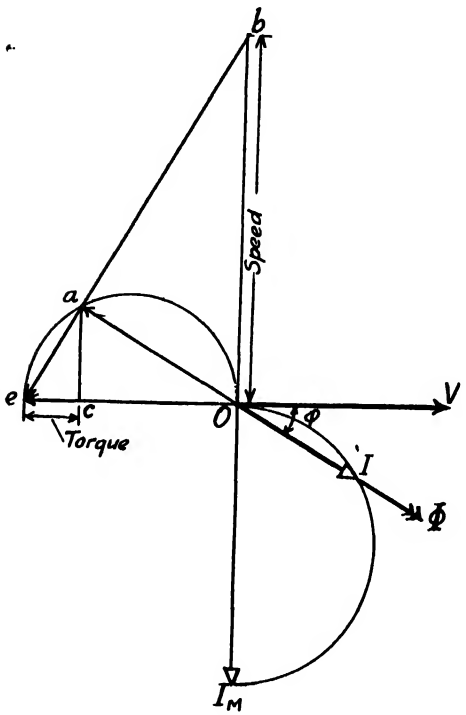


FIG. 46.—General Vector Diagram for Ideal Series Motor.

Thus if the vector diagram of Fig. 41 be re-drawn, as in Fig. 46, with the terminal voltage as the vector of reference, then the locus of the apex, *a*, of the triangle of internal voltages *Oea* is a semicircle (since the angle between the vectors *Oa* and *ae*—which represent the dynamic and inductive E.M.F.s, respectively—is always 90°). Moreover, if the vector OI_M perpendicular to *OV* represents the short-circuit current of the motor (i.e. the current input at standstill when the terminal voltage is represented by *OV*), then if a semicircle is described upon OI_M, and the vector *Oa* be produced into this semicircle the chord *OI* will represent the current input.

The performance of the motor is deduced from this simple vector diagram in the following manner—

The power factor is given by cos ϕ, or *Oa*/*Oe*. Hence, as *Oe* is constant, *the length of Oa is proportional to the power factor.*

The dynamic E.M.F. generated in the armature is represented by *Oa* and is proportional to the product of the flux and the speed, but since the flux is proportional to the current, *Oa* is proportional to (current × speed). Hence the speed is proportional to the ratio *Oa*/current, or *Oa*/*ae*, since *ae* (which represents the inductive E.M.F.) is proportional to the current when the frequency is constant. If a perpendicular be erected on *Oe* at *O*, and *ea* be produced to cut it at *b*, then from the similar triangles *Oae*, *bOe*, *Oa*/*ae* = *Ob*/*Oe*. Hence *the length of Ob is proportional to the speed.*

The power input, and the power output, are both represented by the product *Oe* × *ae* × cos ϕ, or by *Oe* × *ae* × *Oa*, since *Oa* is proportional to cos ϕ. Now if a perpendicular *ac* be drawn from *a* to *Oe*, we have

Oa × *ae* (which product is equal to twice the area of triangle *Oae*) = 2(*Oe* × ½*ac*). Hence *the length of ac is proportional to the power* (input and output).

The *maximum output* is given by the maximum value of *ac*, which is equal to ½*Oe*.

The torque is proportional to (current × flux) or (current)², i.e. ea^2. Now $ea^2 = Oe \times ce$. Hence *the length of ce is proportional to the torque.*

Summarizing, we have—

Oa	is proportional to the		power-factor
ea	,,	,,	current
Ob	,,	,,	speed
ac	,,	,,	watts input and watts output
ce	,,	,,	torque

We are thus able to predetermine the complete performance curves of the motor.

Vector diagram for a commercial series motor. The vector diagram for a commercial motor must include the effects of losses, magnetic saturation, magnetic leakage, and circulating currents. Now all these items vary with the load, so that the predetermination of the performance curves involves the construction of a vector diagram for each operating voltage and load. These diagrams are combinations of the vector diagrams already given. The process, however, is not straightforward, as it is necessary to assume the magnitudes and phases of some of the quantities.

As an example of the method to be adopted in a particular case, we will consider that the performance curves are to be predetermined for a commutating-pole motor for which the full design data are available. If curves are required only for one operating voltage, then we assume a range of values for the flux, and obtain the current and speed from the vector diagram by a process of trial and error. If, however, performance curves are required for a number of voltages, then values are assumed for both flux and speed and the current is determined from the diagram. A set of curves is then constructed giving the volt-ampere characteristics at definite speeds, from which the speed-current curve for constant terminal voltage can be obtained. In the present case, we will suppose that the performance curves are required for only one voltage.

A value is assumed for the main flux (*OY*, Fig. 47*a*). The saturation ampere-turns required for this flux are represented by *OB*. The reaction ampere-turns *OC* (due to circulating currents) are assumed—in magnitude and phase—in order that the field ampere-turns *OA* and the main current *OI* may be determined.

The magnitude and phase of the current in the commutating-pole winding is now determined from data of the winding and the shunting resistance. Thus, in Fig. 47*a*, *OK* represents the current in the shunt resistance, and *OH* the current in the commutating-pole winding. The commutating flux is, therefore, represented by *OZ*, which is in phase with *OH*.*

* If any armature ampere-turns are unneutralized by the compensating winding they must be balanced by a component of the commutating-pole ampere-turns. In this case the commutating flux will not be in phase with *OH*, but with the resultant of the commutating-pole ampere-turns (which are in phase with *OH*) and the unneutralized armature ampere-turns (which are in phase with *OI*).

Next the magnitude and phase of the reaction ampere-turns, *OC*, must be checked. The voltage producing the circulating currents is the resultant of (1) the transformer E.M.F., (2) the reactance voltage, and (3) the commutating E.M.F. These E.M.Fs. can all be calculated and are represented, in Fig. 47*b*, by *Ox* (transformer E.M.F.), *Oy* (reactance voltage), and *Oz* (commutating E.M.F.). Hence *Ow* is the resultant voltage producing the circulating currents, and these currents may be considered to be in phase with *Ow*. The reaction ampere-turns, *OC*, Fig. 47*a*, due to the circulating currents are, therefore, in phase with *Ow*,

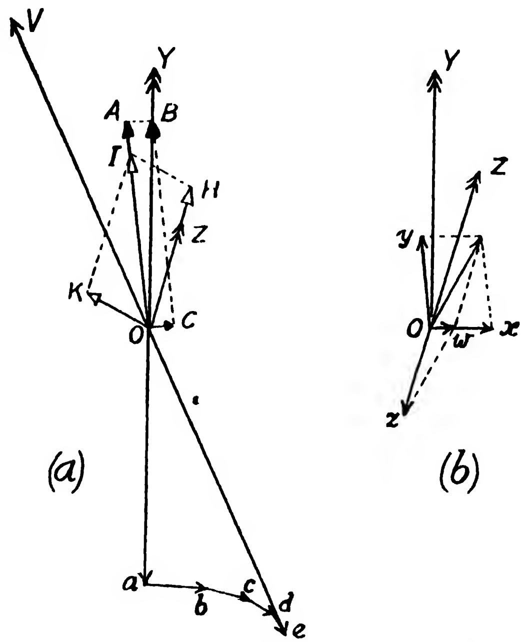


Fig. 47.—Vector Diagram for Commercial Series Motor.

and their magnitude can be determined from the magnitude of *Ow* and data of the armature winding.

The vector diagram is completed by determining the terminal voltage of the motor, which is obtained from the vector polygon of internal E.M.Fs. in the main circuit of the motor. Thus, in Fig. 47*a*, *Oa* represents the dynamic E.M.F. generated in the armature by its rotation in the main flux; *ab*, *bc*, *cd*, *de*, the E.M.Fs. due to the impedances of the exciting, neutralizing, commutating-pole and armature windings taken in order. *Oe* is therefore the resultant internal E.M.F. and is balanced by the terminal voltage *OV*.

General Remarks on Single-phase Series Motors

All types of single-phase motors must be designed with a low flux per pole, low flux-densities, and small air-gaps. The low flux per pole is

required for the purpose of limiting the transformer E.M.F. at starting, while the low flux-densities and the small air-gaps are necessary in order to reduce the exciting ampere-turns and improve the power-factor.

On account of the low flux per pole and the relatively few excitation ampere-turns, the stator core has only a small radial depth of iron.

The **types of armature windings** available are—(1) the multiple-circuit lap (or parallel) winding, (2) the two-circuit (wave or series) winding, (3) the multiple-circuit wave (or series-parallel) winding. Of these windings the first and second varieties are used largely for direct-current machines. For the lower voltage alternating-current commutator motors, however, the single two-circuit winding possesses disadvantages, as, for a given armature voltage and flux per pole, a given number of

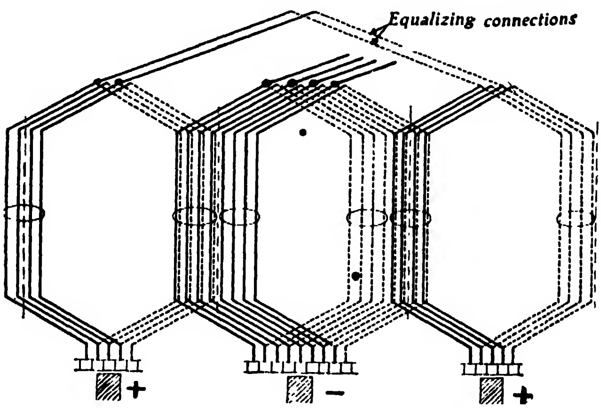


FIG. 48.—Equalizing Connections Applied to Lap Winding in which every Alternate Coil is Equalized.

turns per coil, and a given number of segments short-circuited by a brush, the winding has a higher transformer E.M.F. and a higher reactance voltage than either of the multiple-circuit windings.

The multiple-circuit lap winding, with one turn per commutator segment, is, of course, ideal for obtaining the subdivision of the commutator which is required for commutation purposes. Any unbalance in the magnetic circuits, however, will unbalance the electrical circuits and cause circulating currents. But by means of a liberal number of equalizing connections the circulating currents can be confined to the unbalanced portions of the winding. The equalizing connections interconnect points in the armature winding which are a double pole-pitch apart, and which normally should be at the same potential. Fig. 48 illustrates the principle. In this case every alternate armature coil is interconnected or equalized, the interconnections being made at the back-end of the winding.

Circulating currents due to unbalanced magnetic circuits are not so liable to be set up in multiple-circuit wave (or series-parallel) windings as in multiple-circuit lap windings. For satisfactory results, however,

a multiple-circuit wave winding must be perfectly symmetrical, and in the majority of cases equalizing rings are necessary.*

The **number of slots per pole** in the armature and stator is important from considerations of interference with communication circuits in the vicinity of the traction circuit. This interference is caused by electromagnetic induction from the higher harmonics (having frequencies within the range of normal speech frequencies) of the current in the trolley wires. These harmonics may be caused by the motors, in which case they are due to (1) high-frequency pulsations of the main flux caused by periodic variation in the air-gap reluctance due to the armature slots, (2) high-frequency E.M.Fs. induced in the exciting winding by transformer action from the coils undergoing commutation.

The **air gap** is determined by considerations of power-factor, and has a value between 2 and 4 millimetres (0·08 in. to 0·16 in.) the larger value being permissible only in motors of large output. In comparison, appropriate values for the air-gap of direct-current railway motors are 0·18 in. to 0·25 in.

The **operating voltage** is closely connected with considerations of commutation, the limiting condition being the maximum permissible value of the E.M.Fs. which cause sparking. Of these E.M.Fs. the principal component is the transformer E.M.F., the permissible value of which is dependent upon the subdivision of the armature winding and commutator. Consequently the number of commutator segments will, in general, govern the operating voltage of the motor.

Machines of moderate output can be operated at voltages between 250 and 350 volts, and for large motors voltages up to about 450 volts are practicable.

In consequence, a large contact surface for the brushes is required. Moreover, as the brushes must be of high contact resistance, the losses at the commutator form a fairly large percentage of the total armature losses. Forced ventilation will generally be necessary to dissipate the heat produced by these losses.

With the relatively large losses in the armature, and the losses in the stator, it follows that the efficiency of the motor will be lower than that of a machine of equal output in which the losses are smaller, e.g. a direct-current motor. Thus, in general, the **efficiency of single-phase motors** will be several per cent lower than that of direct-current motors of equal rating. In some cases, however, the increase in weight is not so great as might be anticipated. Obviously, to obtain a correct comparison we must have similar conditions in each case. For example, not only should the output and speed be equal in the two cases, but the efficiency,

* The design of multiple-circuit wave windings with equalizing rings is discussed fully in an article by Professor E. Arnold on "Series-Parallel Armature Windings with Equipotential Connections," *The Electrician*, vol. 57, pp. 322, 450. See also "The Theory of Armature Windings," by Dr. S. P. Smith, *Journal of the Institution of Electrical Engineers*, vol. 55, p. 18.

The general equation for wave windings is

$$y = 2K/p \pm c/p$$

in which y denotes the winding pitch at the commutator, K the number of commutator segments, p the number of poles, and c the number of circuits.

To obtain perfect symmetry it is necessary that p/c and $2K/c$ shall be whole numbers.

temperature rise, and ventilation should also be identical. The following **comparative weights** refer to actual motors of the ventilated type, but the speeds and efficiencies are not identical. The figures, however, will enable a general comparison to be formed between commercial motors for motor coaches and locomotives.

Type.	1-hour Rating.			Efficiency at Rated Load. Per cent.	Power-factor at Rated Load. Per cent.	Weight of Motor without Gears. Lb.
	h.p.	Volts.	r.p.m.			
Direct-current, axle-mounted, mounted, geared motor	160	600	500	87·5*		4300
Single-phase, series, axle-mounted, geared motor	150	235	625	81*	86	5500
Direct-current, frame-mounted, geared, locomotive motor	950	1350	500	94†		12,000
Single-phase, series, frame-mounted, geared locomotive motor	775	410	580	90†	94	13,600

* Including gearing. † Excluding gearing.

Operation of single-phase motors on direct-current circuits. As the alternating-current series motor is identical in principle with the direct-current series motor, it follows that the former type of motor is capable of operating on direct-current circuits. The neutralizing (or compensating) winding, however, must be excited conductively from the main circuit, as this winding is essential to satisfactory operation with direct-current (on account of the high armature ampere-turns). Moreover, with motors of the non-salient-pole type, it will be necessary to provide a commutating field for direct-current operation.

Examples of the operation of alternating-current series motors on alternating-current and direct-current circuits are referred to in Chapter X. The motors are of the Westinghouse type (see p. 102) with salient poles and are installed on certain locomotives of the New Haven Railroad. These locomotives have to operate over the single-phase lines of the New Haven road, and also over the direct-current lines of the New York Central Railroad. The dual operation, however, leads to considerable complication in the control, as well as to increased weight.

EXAMPLES OF SINGLE-PHASE RAILWAY MOTORS

American motors. The simplest type of single-phase railway motor in operation is that developed by the **Westinghouse** Companies. This motor is of the non-commutating-pole type and is built with salient poles. The stator laminations are assembled in a cast-steel frame, which carries seatings for the frame-heads and the axle-bearings. As the frame is not required for magnetic purposes, a skeleton construction is adopted, and large apertures are arranged in the frame at the back of the stator core for the purpose of cooling the latter. The skeleton construction of the frame is well shown in Fig. 49, which refers to a 12-pole motor of 315 h.p. for locomotive service.

Fig. 50 is a cross-section of a 180-h.p., 6-pole, Westinghouse motor,

showing the general design of the armature and stator. An examination of the armature slots will show that they are of the partially closed type and are of two widths. The wider portion of the slot contains the armature conductors proper, while the narrower portion of the slot contains the resistance connections, which connect the armature conductors to the commutator segments. In winding the armature, these resistance connections are first placed in the slots and connected to the commutator segments. The armature coils are then placed in the slots with the open

FIG. 49.—Westinghouse Single-phase Series Motor with Armature Removed.

ends of the coils away from the commutator, i.e. just in the reverse manner to that adopted in winding a direct-current armature. The open ends of the coils are then connected together in the correct order, and are finally connected to the resistance connections.

The object of placing the resistance connections at the bottom of the slots is that the slot may be made narrower at the lower portion, and consequently a larger cross-section is obtained at the root of the tooth than with a slot of uniform width.

The stator windings of these motors are of interest, as they differ in certain respects. The compensating winding is of the distributed type, with concentric coils, and is similar to the winding shown in Fig. 39 (p. 85). In some of the older motors which were intended for operation only on alternating-current circuits, each turn of this winding was short-circuited upon itself, but in modern motors, and also those intended for

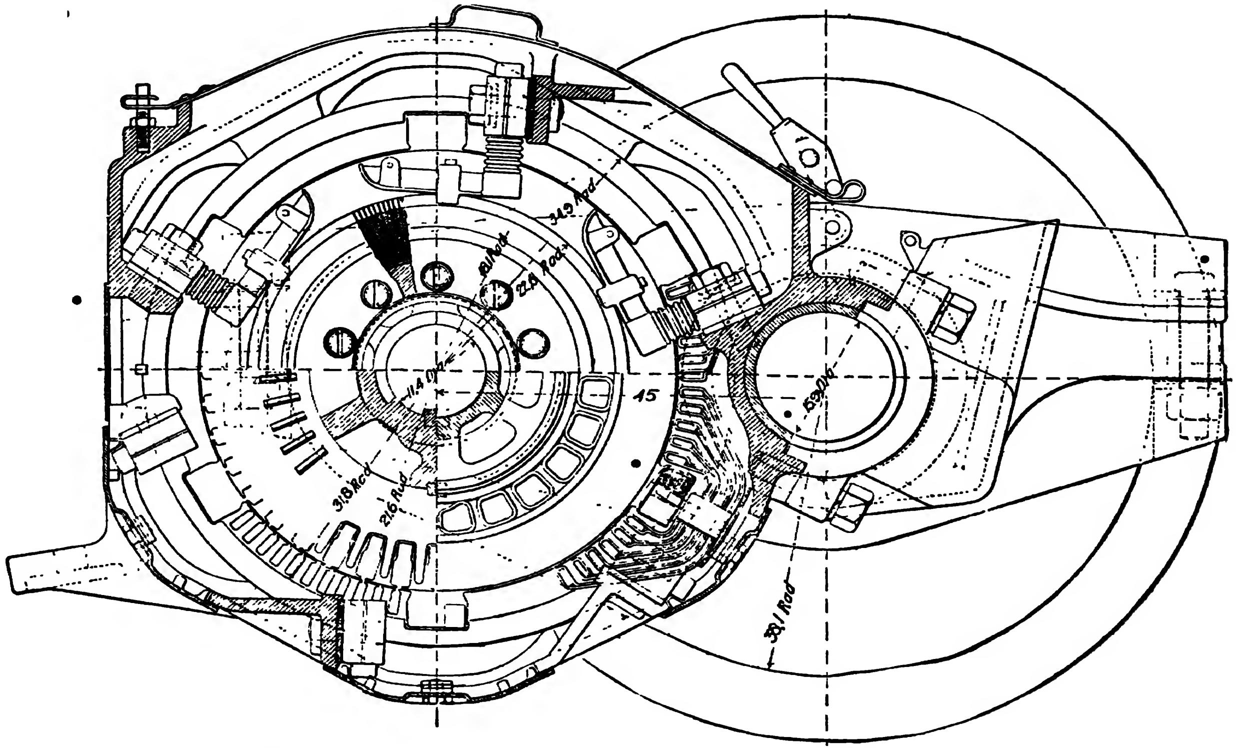


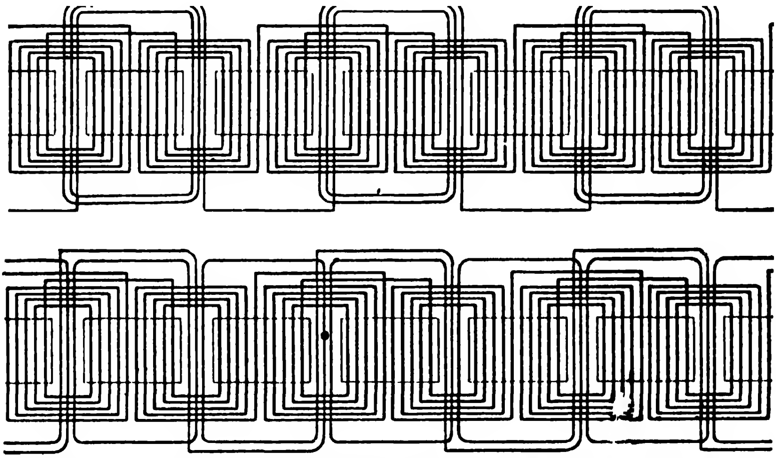
FIG 50.—Cross-section of Westinghouse 180-h.p., 6-pole, 25-cycle, Single-phase Series Motor.
(Dimensions in centimetres.)

operation on direct-current circuits, the winding is connected in series with the armature and exciting windings.

The exciting winding of the motor shown in Fig. 49 consists of six coils, which are wound on *alternate* poles; the coils being connected in series to give like magnetic polarities. The development of a portion of the stator windings is shown in Fig. 51.

The exciting winding of the motor shown in Fig. 50 also consists of six coils, but in this case there is one coil to each pole. The development of the windings is shown in Fig. 52.

The reason for adopting a consequent-pole exciting winding for the larger motor will be apparent from a brief consideration of the inherent



FIGS. 51, 52.—Developments of Exciting and Compensating Windings for 6-pole Motor.

features of single-phase series motors. Thus the saturation ampere-turns per pole required at rated load are low and the current is large. For example, suppose that 1500 ampere-turns per pole have to be supplied with a current of 1000 amperes. If each pole is wound with an exciting coil, then one and a half turns per coil will be required; but if only alternate poles are wound, then three turns per coil will be required.* The latter method is more convenient than the former, and possesses several constructional advantages: thus, (1) all coils are interchangeable (i.e. they are all of the same shape and are wound in the same direction); (2) fewer connections are required between individual coils; (3) the connections between adjacent coils are all at the same end of the machine (see Fig. 50); (4) with split-frame motors, in which the number of *pairs* of poles is even, no split coils are required, the stator being split along the centre line of the pole faces of two unwound poles.

If, however, all poles were provided with exciting coils, viz., one and

* For machines in which the polar surface is continuous the full number of coils may be used, and a convenient number of turns per coil may be obtained by adopting a series-parallel or parallel grouping of the coils. This arrangement is not desirable in machines with salient poles owing to the possibility of circulating currents due to a slight dissymmetry in the positions of the coils or their connections.

a half turns per coil, alternate coils would have to be wound in opposite directions, and the connections between these coils would be alternately at the commutator end and at the pinion end of the machine, as shown in Fig. 52.

The motors are forced ventilated, the air being admitted through an opening at the pinion end of the frame and discharged through apertures at the commutator end of the frame. With the motor illustrated in Fig. 49 the air is circulated through the interior of the motor by means of a fan on the armature and suitable baffle plates, the air being expelled through the apertures in the frame. In this motor the armature core and commutator are provided with longitudinal ventilating ducts only.

European motors. On account of the number of European manufacturers of single-phase motors and the general similarity in their design and construction, we shall give only a few typical examples. In general the stators have non-salient main poles and commutating poles. The exciting winding in some motors is of the concentrated type and in other motors is distributed in two or three slots per pole. The commutating poles are excited according to the method shown in Fig. 44. The armatures have a multiple-circuit armature winding with equalizing connections. Resistance connections are employed only in motors of small and moderate output.

Siemens-Schuckert. Sectional drawings are given in Figs. 53, 54 of a typical axle-mounted geared motor for locomotive and heavy motor-coach service ; and Fig. 55 is a view showing the motor mounted on the axle with the suspension bar in position. The motor is built with eight poles, is forced ventilated, and its continuous rating is 175 h.p. at 325 volts.

Various details of construction are shown in Figs. 53, 54, of which two mechanical details of special interest are the roller bearings for the armature shaft and the mounting of the gear-wheel upon an extension of the hub of the driving wheel. Roller bearings possess two important advantages over sleeve bearings for single-phase motors, viz. (1) the bearings have a long life, and, since the permissible wear is very small, the armature is maintained truly concentric with the stator, so that circulating currents in the (multiple-circuit) armature winding—which would be caused by unbalancing of the magnetic circuits as a result of inequalities of the air gap due to wear of bearings—are reduced to a minimum ; (2) the short axial length of the bearings enables practically the whole of the axial length of the motor frame to be utilized for electrical purposes. The principal electrical features of interest are : The armature has a diameter of 693 mm. (27·3 in.) and is wound with a multiple-circuit bar winding having one-turn coils and equalizing connections, the equalizing rings being located in the back end-flange of the armature. A special feature of the armature winding is the large number (over 400) of coils and commutator segments, in consequence of which the transformer E.M.F. induced in the coils undergoing commutation is of such small magnitude that resistance connections are unnecessary.

The armature core is built upon a spider, which is extended to carry the commutator. Longitudinal ventilating ducts are provided between the core and spider, and also in the commutator. A ventilating duct is

also provided under each slot for the purpose of cooling the armature winding. Air is drawn through these ducts by a double fan fitted to an extension of the front V-ring of the commutator, the air being supplied

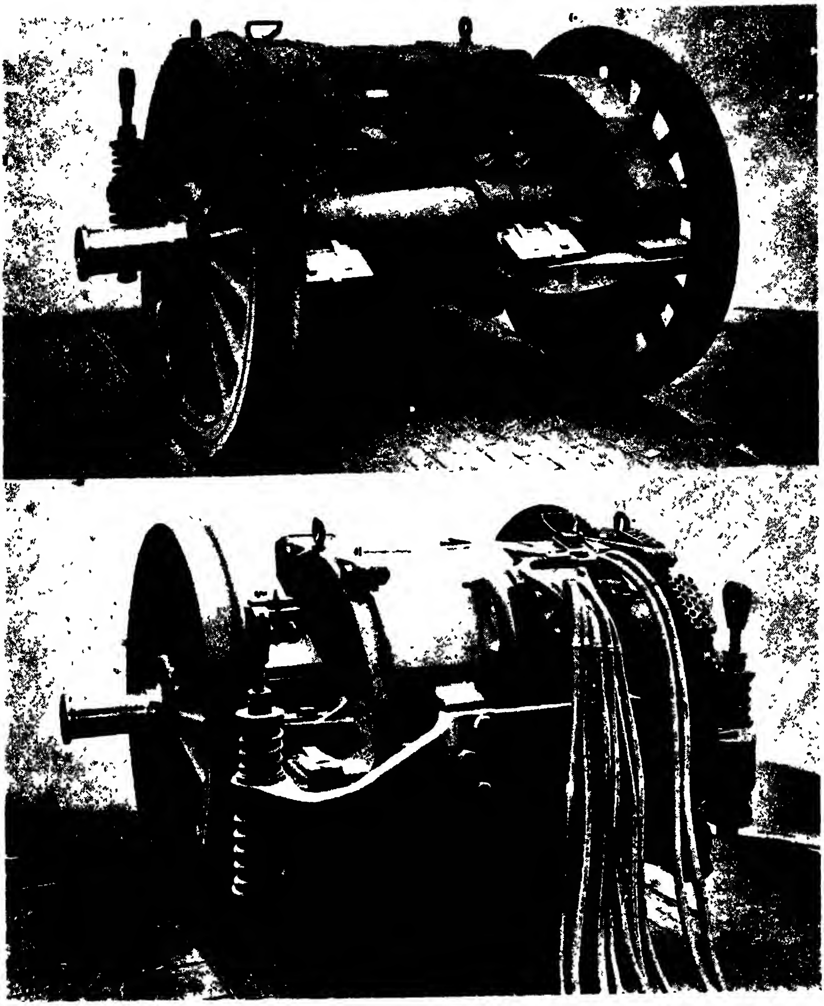


Fig. 55.—Siemens-Schuckert Single-phase Axle-mounted Motor in Position on Driving Axle.

by a blower to the pinion end of the frame and discharged through circumferential apertures in the commutator-end frame-head. The inlet and outlet openings can be seen in the view of the completed motor (Fig. 55).

The air gap is 3·5 mm. (0·138 in.).

The stator has a continuous polar surface which is slotted for the compensating, exciting, and commutating-pole windings. The compensating winding is distributed in six partially-closed slots per pole,

but the exciting and commutating-pole windings are concentrated, and together occupy two slots per pole. These slots are of the open type and are of larger size than those for the neutralizing winding. The intervening tooth forms the commutating pole, a suitable pole arc being obtained by composite slot wedges of which the portions adjacent to the commutating-pole tooth are of magnetic material. A diagram is given in Fig. 56 to show the arrangement of the slots and windings for a pair of poles. The commutating-pole winding is shunted with a non-inductive resistance.

Ventilating slots or tunnels are arranged adjacent to the slots containing the compensating winding (except for those slots adjacent to the axle, where insufficient space is available) and air is drawn through these

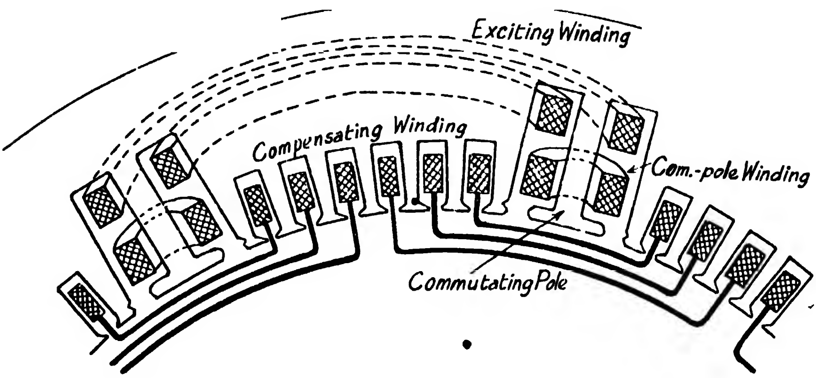


Fig. 56.—Arrangement of Slots and Stator Windings of Siemens-Schuckert Motors.

slots by the double fan fitted to the commutator. This method of cooling is employed extensively by Messrs. Siemens-Schuckert in other types of alternating-current machines.

Larger frame-mounted motors for locomotives possess similar electrical features to those of the motor discussed.

Allmäna Svenska Elektriska Aktiebolaget (Swedish General Electric Co.). A typical large locomotive motor, arranged for frame mounting and side-rod drive, will be considered, the general electrical features of this motor being common to other (smaller) motors of A.S.E.A. manufacture. The motor has 12 poles and its one-hour rating is 830 h.p. at 390 volts, $16\frac{2}{3}$ cycles, the armature speed being 730 r.p.m.

The stator is illustrated in Fig. 57 and possesses the feature that it is constructed independently of the frame. The laminations are rigidly bolted between steel end rings, and the external surface of the core is machined to fit the frame or housing (which is split and is built into the frame of the locomotive).

The compensating winding is distributed in six slots per pole, and the twelve groups of coils are connected in parallel. The exciting winding is distributed in two slots per pole, the coil sides occupying the bottom of the slots containing the commutating-pole winding and also the bottom of the adjacent slots (which are specially deepened) of the compensating winding. Fig. 58 shows the arrangement of the slots and windings.

The commutating-pole winding occupies a portion of the large slots which can be seen in the view of the unwound stator. The twelve groups of the exciting winding are connected in parallel and the twelve commutating-pole coils are also connected in parallel, this (parallel) connection of the

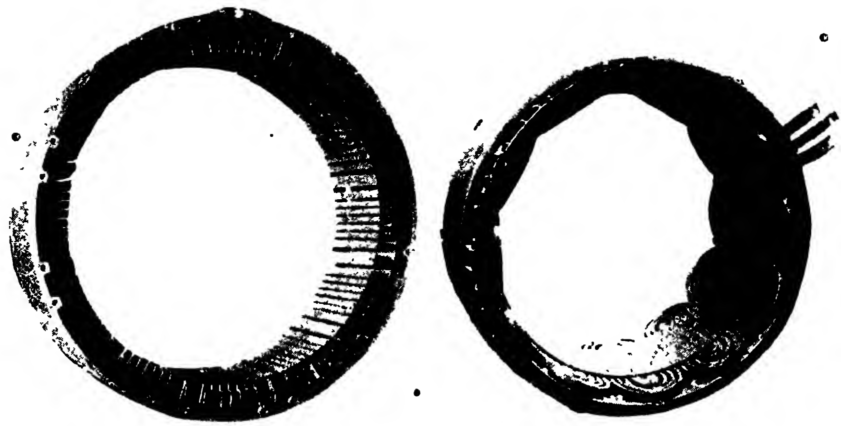


FIG. 57. - Stator Core and Completed Stator of Swedish General-Electric Single-phase Motor.

coil groups being necessary on account of the heavy current of the motor.

All the stator slots are of the partially-closed type, and, in consequence, special arrangements are necessary for carrying out the winding. The exciting winding is placed in position first. The coils are of the "hairpin" type and are shaped and insulated (over the slot portion) before being

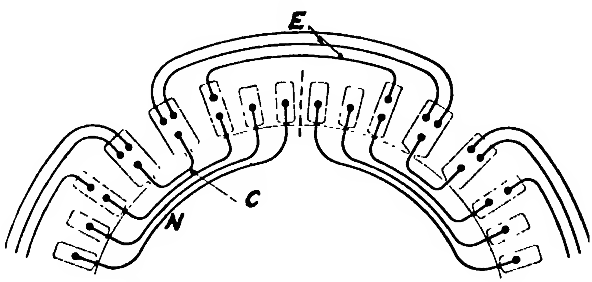


FIG. 58. - Arrangement of Slots and Stator Windings of Swedish General-Electric Single-phase Motors.

(*C*, Commutating-pole Winding; *E*, Exciting Winding; *N*, Compensating Winding.)

pushed into the slots. After insertion in the slots the open ends of the coil are connected and the end connections are completely insulated. The commutating-pole winding is next wound, each turn being drawn through the slots by hand. Finally the compensating winding (the coils of which are of the hairpin type) is placed in position.

The armature, has a one-turn bar winding with twelve circuits. Special features of the winding are (1) the shaping of the front ends of

the coils so that they can be soldered directly into lugs formed on the commutator segments, (2) the large number of equalizing connections, every alternate armature coil being interconnected, (3) the use of solid conductors in the bottom of the slots and split conductors—each having a double cross-over similar to Fig. 19 (p. 56)—in the top of the slots to minimize the eddy-current loss in the conductors, as the slots are of the open type.

The front ends of the armature coils are shaped over the front armature flange in the manner shown in Fig. 59. This construction possesses important advantages over the usual construction—in which the front

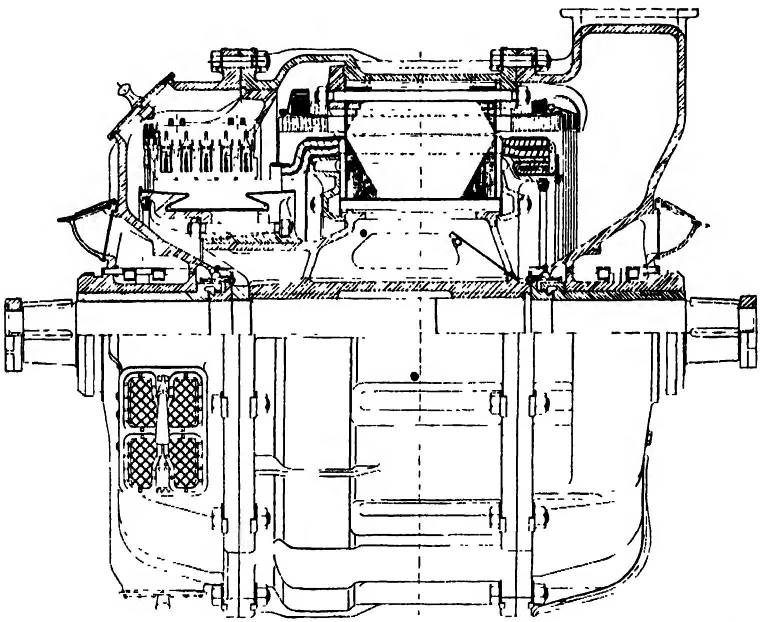


Fig. 59.—Longitudinal Section of Swedish General-Electric Single-phase Motor.

coil-ends are straight and are soldered to commutator risers—as not only is the number of soldered joints at the commutator-end of the armature halved, but these joints are placed where the conditions for cooling are good. The elimination of commutator risers and their soldered joints at the periphery of the armature gives increased reliability, as, owing to space restrictions, high operating temperatures—of the order of 120° to 150° C.—are usually unavoidable in large motors.

The equalizing connections are arranged in the form of a double-layer evolute winding which is located in the back armature flange.

A special feature of the armature core is the skewing of the slots. The slots are skewed a slot pitch in order to prevent pulsations occurring in the main flux, as, with unskewed open slots, periodic variations of the reluctance of the air gap would occur with the rotation of the armature, and would, therefore, cause pulsations of the flux. Such flux pulsations

would produce corresponding pulsations in the induced E.M.Fs., and similar pulsations would occur in the current, which would affect communication circuits running parallel to the trolley wires.

Fig. 59 is a longitudinal section of a smaller (470 h.p.), frame-mounted, twin-geared, locomotive motor which has the same general electrical

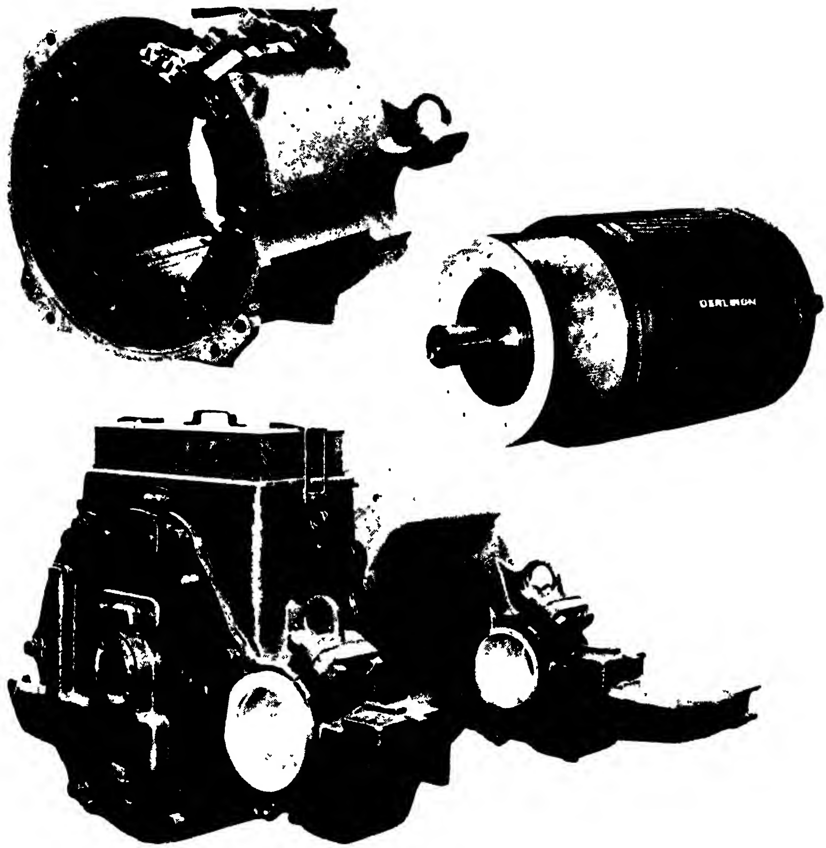


FIG. 60.—Oerlikon Axle-mounted Single-phase Motor.

features as the motor discussed, but is built complete with frame and end shields.

Oerlikon. Typical modern motors for motor-coach and locomotive equipments are shown in Figs. 60, 61, and the completed stator of a 16-pole locomotive motor is shown in Fig. 62. The arrangement of the stator slots and windings is similar to that of Fig. 56, but in the present case the exciting winding is of the whole-coiled type and the compensating winding is distributed in five slots per pole. Completed coils, ready for insertion in the slots, are shown in Fig. 63. The compensating coils are of the "hair-pin" concentric type, and are pushed through the slots. The coils of the exciting winding are placed at the bottom of the wide

slots adjacent to the commutating pole, and the coils of the commutating-pole winding occupy the top of these slots.

The armature winding consists of one-turn, two-piece, bar coils, of which the lower portion is thinner and deeper than the upper portion. The lower bars are formed straight at the commutator end, and are bent at the back end: they are inserted axially into the upper portion of the nearly closed slot (which is wider than the lower portion to correspond

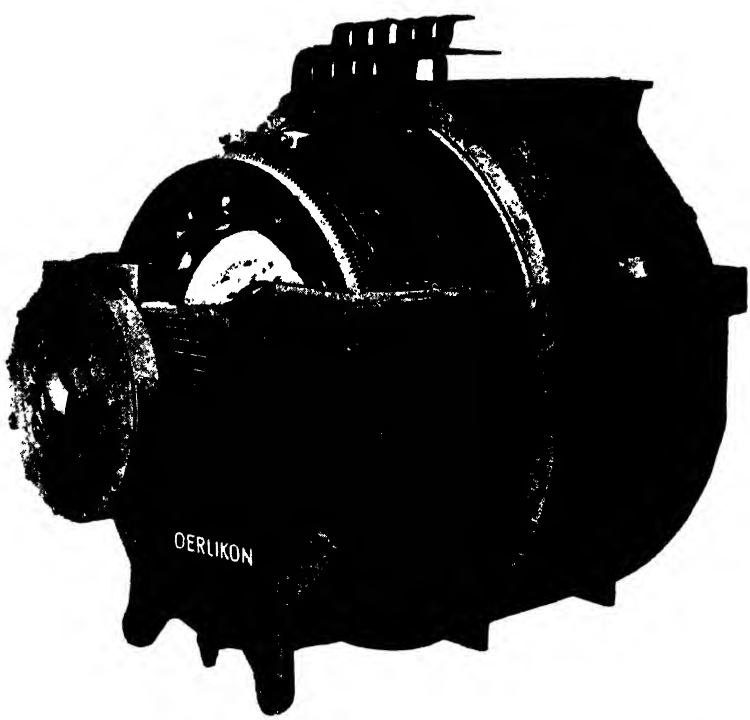


FIG. 61.—Oerlikon Frame-mounted Single-phase Motor for Freight Locomotive.

to the different widths of the coil sides), and are then pressed down radially to the lower portion of the slot. The equalizing rings are constructed as a separate unit with a supporting ring which is bolted to the armature back-end flange.

The brush-gear is very rigidly mounted. The brush-holders of the same polarity are fixed to radial brackets which form part of a massive bus-ring concentric with the commutator. The two bus-rings are fixed to, but insulated from, a yoke-ring, which is seated in a recess formed in the end-shield. The yoke-ring is provided with teeth which gear with a pinion located in the upper part of the end-shield, and the pinion can be operated by means of a handle (normally detached). The yoke-ring is normally locked in position by means of a locking plate engaging a slot in the end-shield. By removing the locking plate and the external connections

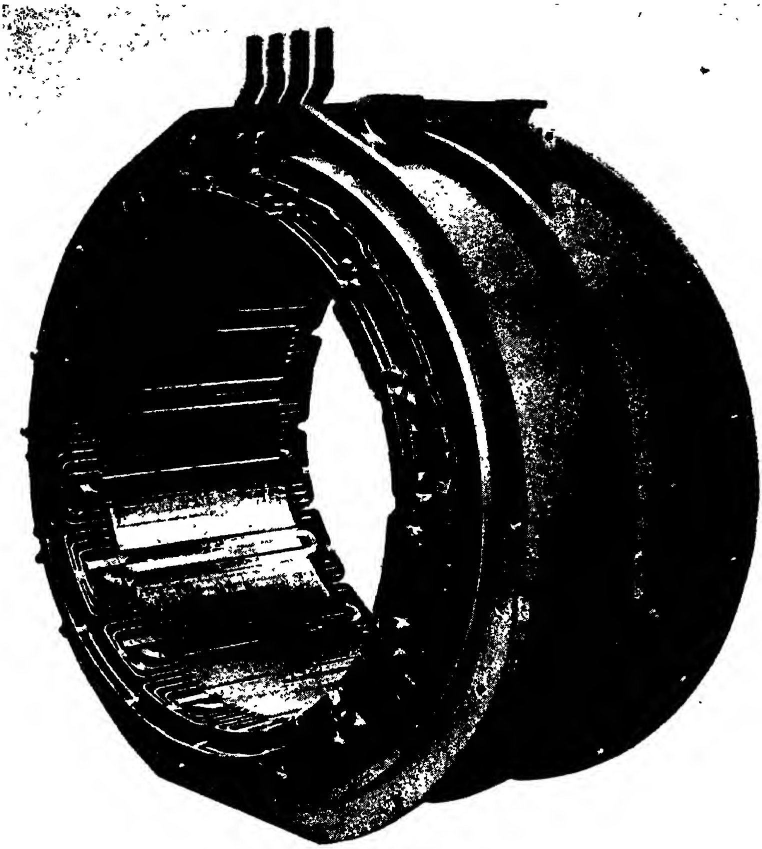


FIG. 62.—Completed Stator of Oerlikon 16-pole Single-phase Motor.

FIG. 63.—Coils of Compensating (a), Commutating-pole (b), and Exciting (c) Windings of Motor illustrated in Fig. 62.

from the bus-rings, any part of the brush-gear may be brought into a position convenient for inspection, cleaning, or repairs.

The characteristic curves of a motor—rated at 545 kW., 380 V., 550 r.p.m.—designed for express passenger locomotive service (individual

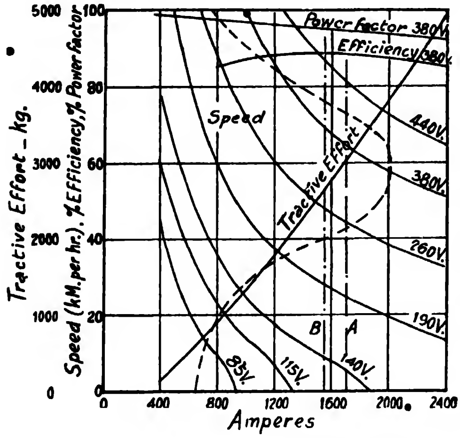


FIG. 64.—Characteristic Curves of Oerlikon Single-phase Motor.
A, 1-hour Rating (380 V.); *B*, Continuous Rating (370 V.).

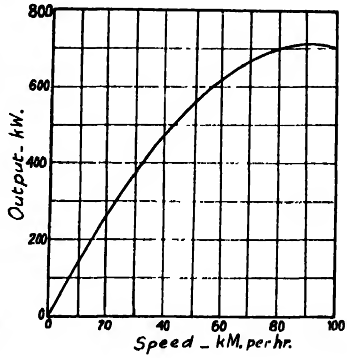


FIG. 65.—Speed-output characteristic of Oerlikon Motor.

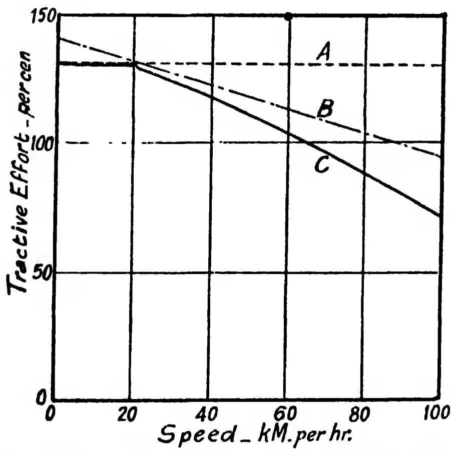


FIG. 65A.—Speed-tractive-effort Characteristics of Oerlikon Motor.

axle geared drive) are shown in Fig. 64. The efficiency curve refers to the output at the armature shaft, and does not, therefore, include the losses in the gearing. The dotted curve indicates the limit of sparkless commutation.

The speed-output curve of this motor is shown in Fig. 65A, the output at various speeds being the continuous output corresponding to a temperature rise of 75° C. (by thermometer) in the hottest part of the motor. The output is limited by the stator temperature at speeds below 20 kM.

per hour, and by the armature temperature at higher speeds. The manner in which the permissible tractive effort is affected by the heating of the various parts of the motor is shown in Fig. 65A, in which the straight line *A* represents the tractive-effort at various speeds which would be permissible from considerations of stator heating only, and curves *B* and *C* the permissible tractive-effort from considerations of commutator and armature heating, respectively.

Brown-Boveri. This firm—which in the early days of single-phase railway electrification successfully developed and applied the Déri brush-shifting repulsion motor to locomotive and motor-coach services*—has,

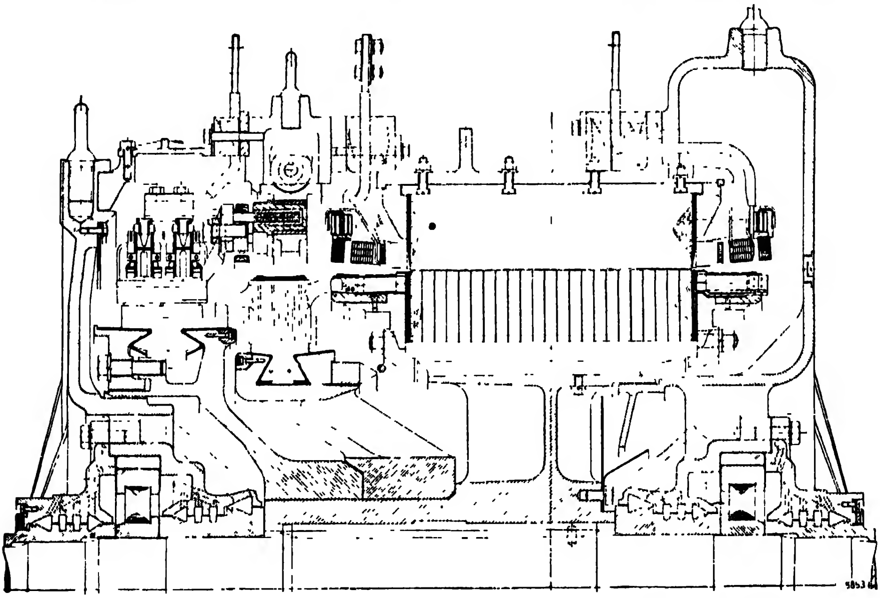


FIG. 66.—Longitudinal Section of Brown-Boveri 690-h.p. Single-phase Motor for Freight Locomotive.

in recent years, concentrated upon the development of the series motor in view of the standardization of this type of motor by the Swiss Federal and other continental railways. Until quite recently the motors were of the usual type, having a distributed compensating winding, an exciting winding, and a series commutating-pole winding shunted with a non-inductive resistance. These motors were developed especially for locomotives and were frame mounted, totally enclosed, and forced ventilated, The armatures of the motors were usually fitted with resistance connections, which consisted of grid-shaped stampings of high-resistance material fixed to mica plates, and mounted between the front connections of the armature and the commutator, as shown in Fig. 66, which is a longitudinal section of a 690 h.p. motor specially designed for

* The applications of Brown-Boveri-Déri motors to these services were described in the first edition of this work. The theory of the Déri motor, together with its control and performance as applied to electric traction, is discussed in *Electric Motors and Control Systems.*

shunting locomotives. This drawing shows the method of mounting the armature in roller bearings and other details of construction.

A few details of the roller bearings—which are of S.K.F. manufacture and have given satisfactory service for a number of years—may be of interest. The diameter of the armature shaft at the bearing seatings is 160 mm., and herring-bone pinions are fitted at each end of the shaft. The bearings had to be designed for a maximum radial load of 5,100 kg. at 550 r.p.m., and to withstand a thrust load of 2,000 kg. for a period of 15 minutes. Moreover, an end play of between 1.5 to 2 mm. was necessary.

The inner races have a flange at one end and are pressed on to the shaft with these flanges facing inwards. The outer races have flanges at each end, and fit into mild steel bushes carried in seatings in the end shields. These bushes are provided with tapped holes to facilitate their removal together with the outer race in case of a replacement being necessary. When the end caps are tightened up the outer races have a lateral play of 0·2 mm.

The seals between the shaft and the end caps are of the labyrinth type, the radial clearance being 0·2 mm. (0·008 in.). A heavy oil is used as a lubricant.

The armature shaft (when cold) was given in each bearing an end play of 0·7 mm., which together with the end play allowed for the outer races, gives a total end play between armature and stator of 1·8 mm. Under working conditions, however, owing to the difference in the expansion of armature shaft and frame, the actual end play is 1·4 mm.

Recently, however, large motors (of about 800 h.p.) have been developed which are a radical departure from the conventional design, the customary distributed compensating winding being omitted and the motors having only exciting and commutating-pole windings. This radical change in the design has been rendered possible by the adoption of a large number of poles. The relatively small pole-pitch thereby obtained permits the armature magneto-motive force to be neutralized by a concentrated winding which can be incorporated with, and in practice actually forms part of, the commutating-pole winding.

The employment of a common winding for neutralizing and commutating purposes requires the provision of a larger number of ampere-turns in the winding than would be necessary if separate neutralizing and commutating windings were adopted, owing to the phase difference which exists between the ampere-turns for neutralizing armature reaction and those for supplying the commutating flux.

For example, the former must be in phase-opposition with the armature ampere-turns, and the latter must have a phase difference of perhaps 30° to 50° with respect to the neutralizing ampere-turns. Hence if the phase of the current in the common winding is adjusted to give the correct phase for the commutating flux, and if $\mathcal{AT}_c$, $\mathcal{AT}_n$ are the ampere-turns necessary separately to supply the commutating flux and to neutralize the armature ampere-turns respectively, then the actual ampere-turns to be provided by the common winding will be $\mathcal{AT}_c + (\mathcal{AT}_n/\cos\theta)$, where θ is the phase difference between the neutralizing and commutating ampere-turns. But this apparent disadvantage is more than compensated by the simpler and cheaper construction, and in practice the amount of copper in the stator is actually smaller than in a stator of the same dimensions provided with separate compensating, exciting, and commutating-pole windings, owing to the very short end connections of the new arrangement of the windings.

Fig. 67 shows a partially-wound stator which has 16 poles. The

windings are located in large partially-closed slots, which divide the polar surface of the stator into main and commutating poles. The exciting winding is placed in the bottom of the slots first and the commutating-pole winding is then wound in the upper portion of the slots (i.e. nearest to the armature). This arrangement, although necessitating drawn-in hand windings, gives not only lower leakage reactances for the commutating-pole, exciting, and armature windings, together with a lower magnetic leakage between the commutating and main poles, but also

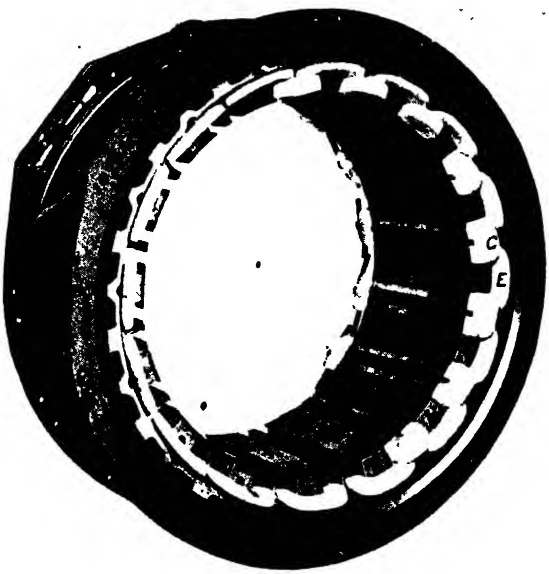


Fig. 67.—Partially-wound Stator of Brown-Boveri Single-phase Motor With Exciting (E), and Combined Compensating and Commutating-pole (C) Windings.

smaller I^2R losses in the commutating-pole circuit than if the windings were placed side by side in the slots.

The armature has a multiple-circuit winding with equalizing connections, and the front ends of the coils are shaped over the front armature flange and soldered directly into lugs formed on the commutator segments. Moreover, these connections are exposed, so that the cooling air which is blown through the armature core may escape through them and assist in cooling the commutator.

Fig. 68 shows external views of the motor. The end-shields are of cast steel; they carry the armature (sleeve) bearings and are provided with feet for supporting the motor between the side frames of the locomotive.

The brush-gear is fixed to a yoke-ring which is centred in the commutator end-shield and is fitted with a worm and worm-wheel, so that, when necessary, any set of brushes can be brought to the inspection opening (which is normally closed by a segmental cover of aluminium).

The power is transmitted through single-reduction spur gearing, which

is arranged *outside* the driving wheels, according to the Brown-Boveri system described in Chapter XVIII. Thus the whole space between the side frames of the locomotive is available for the motor.

The characteristic curves of the motor are given in Fig. 69; the curves refer to the output at the armature shaft, and the efficiency

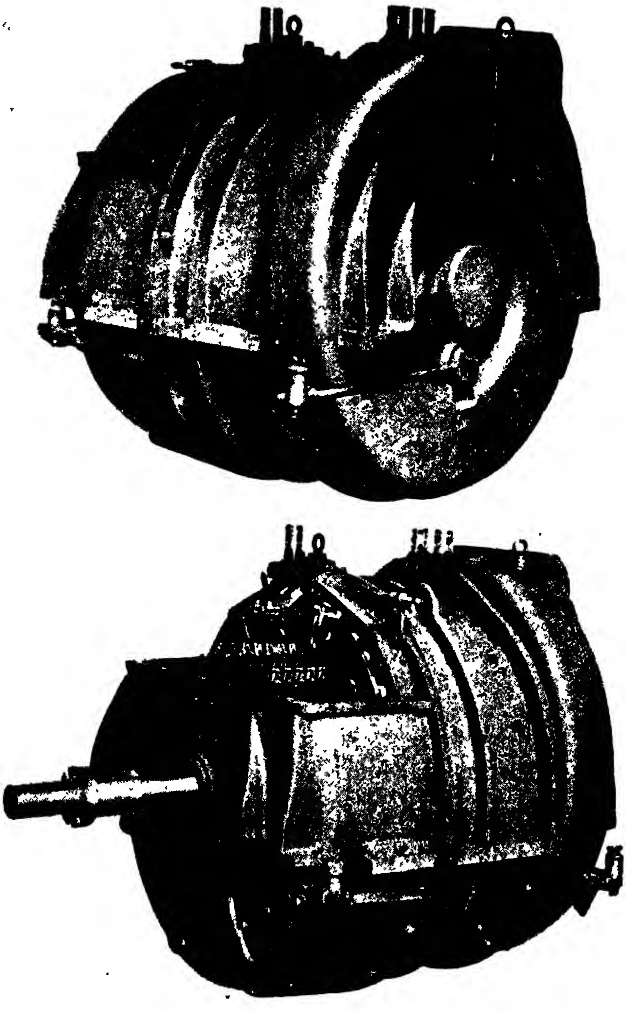


FIG. 68.—Brown-Boveri Single-phase Motor for Express-passenger Locomotive.

includes all the losses in the motor but does not include the losses in the gearing nor the power required by the external blower.

The advantages of the new design compared with the conventional design with fewer poles and a distributed compensating winding may be summarized thus—

Simpler and cheaper construction; larger output for given external dimensions and speed (due to a longer armature core being possible in consequence of the shorter overhang of the end connections and the shorter commutator); higher efficiency (due to the lower I^2R losses in the windings for a given output in the two cases); good commutation over a speed range (with voltage control) of 1 : 3; a reduction of about 20 per cent in the exciting ampere-turns; a steeper speed-current

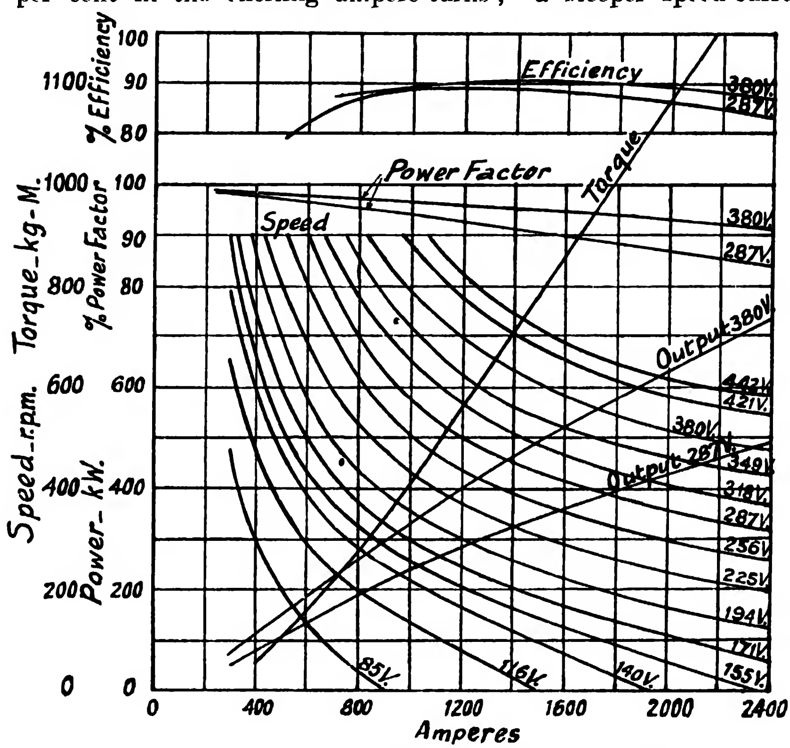


FIG. 69.—Characteristic Curves of Brown-Boveri Single-phase Motor.

curve; and less distortion of the current wave-form as a result of the elimination of slots in the main pole faces.

The good commutation over the wide speed range is due to the smaller transformer E.M.F. in the commutated coils of this motor (owing to the employment of a smaller flux per pole in consequence of the larger number of poles), and also to the wave-form of the current being almost sinusoidal.

The power-factor of the motor is practically equal to that of a motor of the same rating with the conventional distributed compensating winding, as the reactance caused by the imperfect neutralization of the armature magneto-motive force is practically balanced by the lower reactance of the exciting winding.

The wide speed range over which good commutation is obtained is especially advantageous for locomotive service, as it enables a given locomotive to operate satisfactorily mixed traffic, e.g. express passenger traffic, local (medium speed) passenger traffic, and goods traffic.

CHAPTER VI

POLYPHASE TRACTION MOTORS

THE only type of polyphase motor which has been applied to electric traction is the three-phase induction motor.* This motor possesses a "shunt" (or constant-speed) characteristic, and, when speed regulation is required, the regulation can only be obtained *economically* by the use of auxiliary machines or additional windings on the motor. Therefore the polyphase induction motor is entirely unsuitable for suburban services. The machine is, however, suitable for main-line long-distance services, where the stops are infrequent and the acceleration is unimportant. Moreover, with polyphase induction motors, efficient regenerative braking can be obtained without complication of the control apparatus, and therefore these motors are eminently suitable for service on mountain railways. In fact, it is on railways of this nature that the greatest development of the three-phase traction motor has occurred.

The adoption of three-phase motors requires at least two trolley wires (the track rails forming the third conductor), but in the case of mountain railways the disadvantages of the duplication of the overhead construction are compensated by the facility with which regenerative braking can be obtained.†

Although the constant-speed type of polyphase motor may be suitable for handling certain classes of traffic, nevertheless, for satisfacory working, it is desirable to provide two or more efficient running speeds. The provision of a number of efficient running speeds will also lead to economy during the starting and accelerating periods.

In practice, the economical methods of regulating the speed of polyphase induction motors are limited, and for the purpose of discussing these limitations we will now state the fundamental relations between the speed and torque, as given by the following equations—

(1) Speed . $n = n_s(1 - s) = f(1 - s)/\tfrac{1}{2}p$ . . . (19)

(2) Torque . $\mathfrak{T} = K\Phi I_2 \cos\phi_2 = K\Phi s E_2 R_2/(R_2{}^2 + s^2 X_2{}^2)$
$= K_1\Phi^2 s R_2/(R_2{}^2 + s^2 X^2{}_2)$ (20)

(3) Power input to rotor . $P_2 = E_2 I_2 \cos\phi_2$ . . (21)

(4) Power dissipated in rotor—

(i.e. rotor I^2R loss) . $P_R = sE_2I_2\cos\phi_2 (= sP_2 = P_2 - P_M)$ (22)
$= K_3 sf\mathfrak{T}/p$ . . . (22*a*)

* Although the three-phase variable-speed commutator motor has been applied to industrial service, it has received no application to traction service. This motor, however, is more costly, larger, and less efficient than an induction motor of equal rating, while the necessity for a commutator and brushes introduces difficulties into the design and operation of a similar nature to those connected with single-phase commutator motors.

The types of polyphase commutator motors and their characteristics are discussed very fully by Mr. N. Shuttleworth in a paper on "Polyphase Commutator Motors" (*Journal of the Institution of Electrical Engineers*, vol. 53, p. 439).

† Regenerative braking is also possible with single-phase commutator motors —as explained in Chapter XII—but this entails additional control apparatus.

(5) Mechanical output $P_M = (1-s)P_2 = (1-s)E_2I_2 \cos\phi_2$
$= K_2(1-s)\mathfrak{T}$ . . . (23)

(6) Electrical efficiency of rotor $\eta_2 = 1-s$ . . . (24)

where n is the speed of the rotor in revolutions per second,
n_s the synchronous speed of the revolving field in revs. per sec.,
f the frequency of the supply current,
p the number of poles,
s the slip $(= (n_s - n)/n_s)$,
$\mathfrak{T}$ the gross torque,
Φ the flux per pole,
E_2 the E.M.F. induced in the rotor at standstill,
I_2 the current in the rotor,
ϕ_2 the phase difference between E.M.F. and current in rotor,
R_2 the resistance per phase of the rotor,
X_2 the reactance per phase of the rotor at standstill,
and K, K_1, K_2, K_3 are constants.

At starting ($s = 1$) the torque is given by

$$\mathfrak{T}_s = K_1\Phi^2R_2/(R_2^2 + X_2^2) \quad . \quad . \quad . \quad . \quad . \quad (20a)$$

and at normal speed the torque is approximately given by

$$\mathfrak{T}_n = K_1\Phi^2 s/R_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20b)$$

since, owing to the small value of the slip under these conditions—which is of the order of 0·03—the reactance (sX_2) of the rotor circuit is usually very small in comparison with the resistance of this circuit.

The torque can also be expressed in terms of the rotor I^2R loss (P_R). Thus, from equation (22a) the torque at starting ($s = 1$) is given by $\mathfrak{T}_s = pP_R K_4$, and the torque when running is given by $\mathfrak{T}_r = pP_R K_4/s$, where $K_4 = 1/fK_3$.

Speed control. Considering only supply systems of constant frequency equation (19) shows that there are two methods of regulating the speed of an induction motor, viz. (1) by varying the slip, (2) by changing the number of poles. The speed variation obtained by the separate use of either of these methods is limited, but by the combination of the two methods a large speed variation can be obtained.

When speed control is obtained by varying the slip the maximum speed is equal to the synchronous speed: but when pole changing is employed the motor will possess a constant-speed characteristic for each set of poles, and intermediate speeds will have to be obtained by varying the slip.

When speed regulation at constant torque is to be obtained by variation of the slip, the electrical power expended in the rotor circuit is proportional to the slip. (Equation (22a).) But this energy need not be wasted in rheostats, as it can be utilized in the form of mechanical or electrical energy by means of either another induction motor or a commutator machine connected in cascade with the motor to be regulated. In each case the slip energy must be delivered either to the shaft of the main induction motor or to the supply system, but in the latter case a motor-generator set is required, in addition to the auxiliary or cascade

machine, to convert the slip energy into electrical energy having the same frequency and voltage as the supply system. Although each system has been applied to industrial plants, only the cascaded-induction motor system has been applied to electric traction, and the principal developments in this direction have occurred on the Continent.

Cascaded-induction motors. The cascade connection of the main or primary motor (the speed of which is to be regulated) with another induction motor (called the secondary motor) requires the two rotors to be mechanically coupled or geared together. For example, the rotors may be mounted on the same shaft or on separate shafts, but in the latter case the shafts must be geared or mechanically connected together.

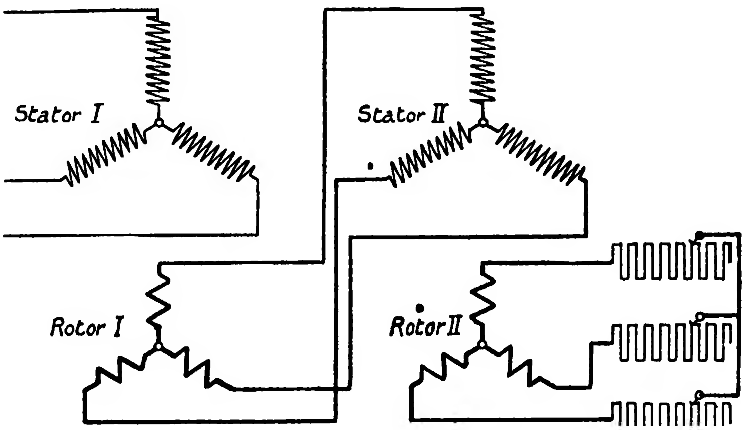


FIG. 70.—Cascade Connection of Two Induction Motors.

The rotor of the primary motor must be provided with slip rings, and the rotor of the secondary motor may be of a similar type, or of the squirrel-cage type.

In the cascade connection the stator winding of the primary motor is connected to the supply. The slip-rings are connected to the stator winding of the secondary motor, and the rotor winding of this motor is connected to a rheostat, as indicated in Fig. 70.* The rheostat enables the speed of the set to be regulated up to the cascade synchronous speed, which, if each motor has the same number of poles, is equal to one-half of the synchronous speed of the primary motor.

Thus, consider the set running light, with the rotor of the secondary motor short-circuited, and let p_1, p_2 denote the number of poles in the primary and secondary motors respectively. Then, if f is the frequency of the supply system and s is the slip in the primary motor corresponding to cascade synchronous speed, the speed of this motor will be $f(1-s)/\frac{1}{2}p_1$ revolutions per second. The frequency supplied to the secondary motor

* It is not essential that the rotor of the primary motor be connected to the stator of the secondary motor, as the two rotor windings may be connected together and the rheostats connected to the stator winding of the secondary motor.

is fs_2, and therefore the synchronous speed of this motor will be $fs/\frac{1}{2}p_2$ revolutions per second.

Since the two rotors are mechanically coupled together, the ratio of their speeds is constant, and, if both rotors are fixed to the same shaft, then $fs/\frac{1}{2}p_2 = f(1-s)/\frac{1}{2}p_1$, whence $s = p_2/(p_1 + p_2)$.

If each motor has the same number of poles, the minimum slip of the primary motor cannot have a value less than 50 per cent, i.e. the cascade synchronous speed is one-half of the synchronous speed of the primary motor. Generally the **cascade synchronous speed**, in revolutions per second, is given by

$$n_c = f/\tfrac{1}{2}(p_1 + p_2)^* \quad . \quad . \quad . \quad . \quad (25)$$

It is possible, therefore, to obtain two economical speeds, but intermediate speeds will have to be obtained by regulating the slip by means of rheostats. If, however, both motors are wound with pole-changing windings a larger number of economical speeds can be obtained.

The **mechanical outputs** of the cascaded motors when running with normal slip in the secondary motor are approximately proportional to the numbers of poles in the motors. Thus if P_2' is the power supplied to the rotor of the primary motor, and s_1 is the slip, the mechanical output of this motor is $P_M' = (1-s_1)P_2'$. Hence, if the I^2R losses in the rotor and stator circuits of the primary and secondary motors are ignored, the power supplied to the rotor of the secondary motor is equal to

$$P_2' - P_M' = s_1 P_2';$$

and, therefore, the mechanical output of this motor is

$$P_M'' = (1-s_2)s_1 P_2'$$

where s_2 is the slip of the secondary motor.

Whence
$$\frac{P_M''}{P_M'} = \frac{(1-s_2)s_1}{1-s_1} = \frac{n/n_c}{n/n_s} \cdot \frac{n_s - n}{n_s} = \frac{n_s - n}{n_c},$$

where n_s, n_c are the synchronous and cascade synchronous speeds respectively, and n is the speed of the set.

If, however, the slip, s_2, is small, n is approximately equal to n_c, and in this case

$$\frac{P_M''}{P_M'} = \frac{n_s - n_c}{n_c} = \frac{p_2}{p_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

Hence, if each motor has the same number of poles, the total power developed by the cascaded motors is divided approximately equally between the two machines. Actually, however, owing to losses in the stator and rotor circuits, the power developed by the secondary motor will be slightly less than that developed by the primary motor.

* In deriving this equation, we have tacitly assumed that the direction of rotation of the motors (when supplied separately) is the same. If the secondary motor is connected so that it tends to rotate in the opposite direction to the primary motor, the motors are said to be connected in "differential cascade," and the cascade synchronous speed under these conditions will be given by

$$n_c = f/[\tfrac{1}{2}(p_1 - p_2)]$$

The **principal objections to speed regulation by the cascade system** are—(1) two motors are required,* which, if they are to operate in parallel (at speeds between cascade synchronous speed and full speed), must have the same number of poles, while the stator windings of the secondary motor must be capable of operating with the full supply voltage and also with the rotor voltage (corresponding to cascade synchronous speed) of the primary motor ; (2) the low power-factor of the combination.

It is not essential that the two motors should have separate frames, as, when the rotors are mounted on the same shaft, the two stators may be combined in a common frame. This form of construction, however, can only be employed for railway motors of small and moderate outputs

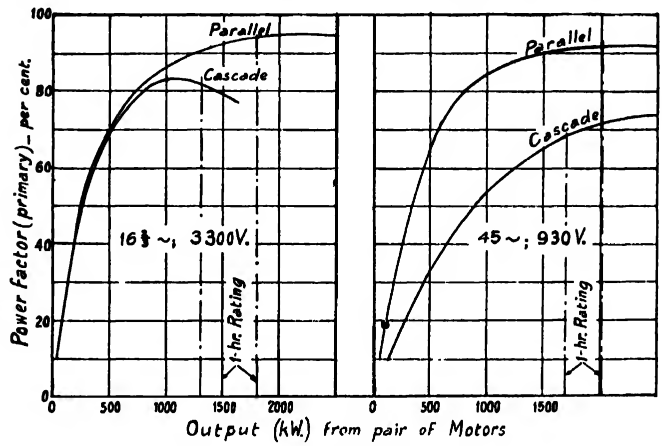


FIG. 71. Power-factor Curves for Cascade and Parallel Operation of Brown-Boveri 1000 kW. Induction Motors.

on account of the space restrictions imposed by locomotives. It was employed by Ganz & Co. in some of the early locomotives built for the Italian State Railways, but is not now employed on account of the large sizes of the motors in the present-day locomotives.

The low power-factor is due to the magnetizing current of the secondary motor being superimposed on that of the primary motor. It is necessary, therefore, to design each motor for a low magnetizing current and low reactance, the attainment of which is facilitated by a low frequency of supply (e.g. 16⅔ cycles).

The effect of frequency on the power-factor of cascaded motors is shown in the curves of Fig. 71, which refer to large (1300 h.p.) 16⅔- and 45-cycle, three-phase, locomotive motors built by the Tecnomasio Italiano Brown-Boveri.

The power-factor of the motors when operating in cascade and in parallel is also shown, and the reduction in power-factor due to cascade operation can, therefore, be determined.

* In some special cases cascade operation can be obtained from a single motor with special windings, but motors of this type (known as the " Hunt Cascade Motor ") have only been developed for industrial service.

Speed control by pole changing. The method of regulating the speed of polyphase motors by changing the number of poles has been developed for electric railway work by Messrs. Brown-Boveri, and by the Westinghouse Companies in Italy and America.

The **number of synchronous speeds** which can be obtained from a single motor by pole-changing are—

Two (in some special cases *three*), when a single stator winding is used: and *four* when two separate stator windings are used, each winding being arranged for pole-changing.

When a single pole-changing stator winding is adopted, the rotor may be of either the phase-wound type, with slip-rings, or the squirrel-cage type: the former requiring either two separate windings (and slip-rings) or a single pole-changing winding. But when two pole-changing stator windings are adopted—to obtain four synchronous speeds—the rotor is usually of the squirrel-cage type, and starting is performed by varying the voltage applied to the stator.

Pole-changing windings (i.e. single windings which may be re-connected—by arranging certain external connections—so as to give different numbers of poles) may be developed from all standard types of polyphase windings by arranging the connections between coils and phases in a certain manner.

The simplest arrangement of windings and connections is obtained when the poles are changed in the ratio of 2 : 1. In this case only six external leads are required between the motor and pole-changing switch. On the other hand, when the poles are to be changed in the ratio of 1·33 : 1 without changing the number of phases, it is necessary, in changing the poles, to re-arrange the connections of a considerable portion of the winding, so that a large number of external connections are necessary between the motor and pole-changing switch.

Double-layer windings are usually employed when the number of poles is to be changed without changing the number of phases. These windings possess the following features—(1) All coils are of the same size and shape; (2) the number of coil groups per phase is equal to the number of poles; (3) the end connections may either project axially to form a " barrel " winding, or be bent up at right angles to the shaft so as to shorten the overall length of the machine; (4) the coil pitch may be made equal to any whole number of slots without disturbing the symmetry of the winding, thereby permitting the use of fractional pitch windings, which possess a number of advantages over full-pitch windings.

Fractional-pitch double-layer windings are of considerable value when pole-changing is required, as, by a suitable choice of the pitch, a good flux wave-form can be obtained for each set of poles, and all turns are effective for both speeds.

An important feature in connection with fractional-pitch windings for changeable-pole motors, in which two sets of poles in the ratio of 2 : 1 are required, is that the winding must be designed for the *smaller* number of poles, as, if the winding were designed for fractional pitch and the full number of poles, the pitch corresponding to the smaller

number of poles would be below 50 per cent, so that considerable differential action would take place and the performance of the motor would be unsatisfactory. The larger number of poles is obtained by reversing the direction of current in one-half of the winding.

For example, if four and eight poles are required, the winding is designed for four poles, with a coil pitch of, say, two-thirds the pole pitch. When the connections are changed to give eight poles the coil pitch will be ($2 \times \frac{2}{3} =$) $1\frac{1}{3}$ times the (eight-) pole pitch. Therefore the "coil-pitch" or differential factor (which is equal to $\sin \frac{1}{2}\theta$, where θ is the coil pitch in electrical degrees) has the same value in each case.

A diagram showing the connections and development of this winding is given in Fig. 72, which, for clearness, has been drawn with one slot per pole per phase and one turn per coil. Each phase of the winding consists of four coils, of which alternate coils are connected in series

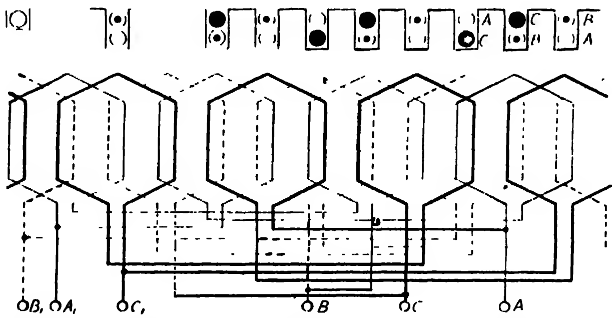


FIG. 72.—Connections and Development of Fractional-pitch Pole-changing Winding to give 4 and 8 Poles.

and the two pairs so obtained are again connected in series, a tapping being brought out from the centre point of the phase. The connections between the coils are arranged so that, when current is circulated through all the coils in series, eight poles will be produced (since the currents in conductors occupying adjacent slots will have opposite directions), but, when current is circulated through the two halves of the phase connected in parallel, four poles will be produced, due to the reversal of the currents in alternate coils. The phases are delta-connected (with all coils in series) for the lower speed (8 poles), and are star-connected (with the two halves of each phase connected in parallel) for the higher speed (4 poles), as shown schematically in Fig. 73. It should be observed that no reversal of the phases, in relation to the line wires, is necessary when the number of poles is changed.

An analysis of the M.M.F. distribution for the two sets of poles will show that all the turns of the winding are effective for both speeds, and if the M.M.F. wave-forms are similar, the fluxes per pole will be in the ratio of 1 : 1·15.

Thus, let N denote the number of turns in series per phase for the larger number of poles ; Φ_8, Φ_4 the fluxes per pole corresponding to the larger and smaller numbers of poles, respectively ; E the supply voltage ;

then, ignoring the internal voltage drop due to resistance and reactance, we have

$$\Phi_8 = E/KN\,;\ \ \Phi_4 = (E/\sqrt{3})/(K\,.\,\tfrac{1}{2}N)$$

Whence $\Phi_4/\Phi_8 = 2/\sqrt{3} = 1{\cdot}15$.

Hence the flux densities in the stator and rotor cores, when the motor is operating at high speed, are only 15 per cent greater than those corresponding to low-speed operation, so that the magnetic material is utilized to the best advantage.

Assuming the same permissible electric loadings at each speed and neglecting losses, the output at the higher speed will be about 15 per cent greater than that at the lower speed. In practice, due to the better natural ventilation at the higher speed, the output at this speed will be approximately 30 per cent greater than that at the lower speed.

The influence of the number of poles on the power-factor of a changeable-pole motor is shown in the curves of Fig. 90 (p. 145), which refer to a large 16-cycle, 3000-volt Brown-Boveri motor having two stator

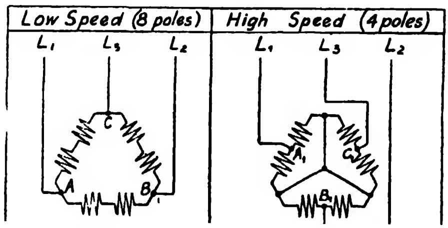


FIG. 73.—Method of Grouping Pole-changing Stator Windings.

windings, each of which is arranged for pole-changing according to the above method.

Stator and rotor windings for combined pole-changing and cascade methods of speed regulation. The above discussion on pole-changing windings has been confined to windings from which two sets of poles, in the ratio of 2 : 1, can be obtained. In some cases, however—particularly where the pole-changing and cascade methods of speed regulation are combined—it is desirable to be able to change the poles in a smaller ratio than 2 : 1. For instance, four running speeds, in the ratio of 1 : 1·33 : 2 : 2·66 (or, alternatively, 1 : 1·5 : 2 : 3) will be more suitable for general railway service than three running speeds in the ratio of 1 : 2 · 4. Now to obtain four synchronous speeds, in the ratio of 1 : 1·33 : 2 : 2·66, by the combination of pole-changing and cascade control, the stator and rotor windings of each motor must be such that two groups of poles—in the ratio of 1·33 : 1—can be obtained. Moreover, the voltage relations for both windings must be suitable for cascade as well as parallel operation. A cursory consideration of the problem would result in the provision of two sets of stator and rotor windings on each motor. This solution cannot be regarded as entirely satisfactory, since only 50 per cent of the total copper in the machine would be utilized, while the deep slots in the stator and rotor would result in a high reactance and a low power-factor. Moreover, the duplication of the control

apparatus would lead to an undesirable increase in the weight and maintenance of the equipment.

An entirely satisfactory solution, however, is possible, and the required speed variation can be obtained, with satisfactory performance at all speeds, by means of a *single winding on each stator and rotor*. Two alternative methods are practicable: one method—which is applicable to double-layer windings—requires two pole-changing switches, one for each (stator and rotor) winding: the other method—which is applicable to single-layer windings—requires only a pole-changing switch for the stator winding, but necessitates a change in the number of phases, as well as poles, of this winding in order that a single rotor winding, with two sets of slip-rings, may be suitable for both sets of poles. The practical application of both methods is found in the equipments of the four-speed passenger locomotives built by the Tecnomasio Italiano Brown-Boveri* and the Società Italiana Westinghouse† for the Italian State Railways.

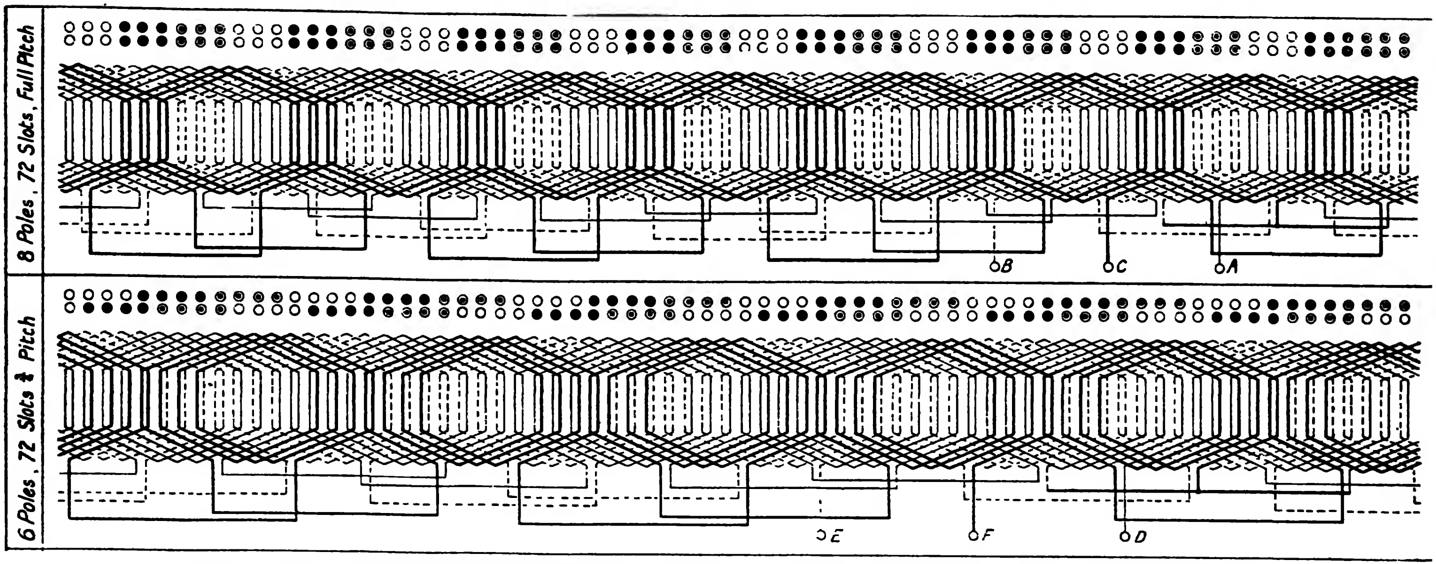
We will consider first the **method in which the number of poles is changed,** in the ratio of 8 : 6 (i.e. 1·33 : 1), **without changing the number of phases.** To obtain this result we require a pole-changing winding of the double-layer type. If the winding is designed for full pitch when connected for the larger number of poles, then the pitch corresponding to the smaller number of poles will be fractional and equal to 75 per cent of the pole pitch. In order to obtain symmetrical windings for both sets of poles the number of slots per phase must be exactly divisible by both pole numbers. Thus, for the present case, the permissible numbers of slots per phase are 24, 48, 72, etc. Hence, confining our attention only to three-phase machines, the minimum permissible number of slots in the stator or rotor is ($3 \times 24 =$) 72.

Now a double-layer, three-phase, winding for this number of slots requires 72 coils, there being 24 coils in each phase. For eight poles these coils must be arranged in eight groups, each group consisting of three coils, and for six poles they must be arranged in six groups, each group consisting of four coils. Diagrams showing the connections between the groups of coils for the 8-pole and 6-pole combinations of the winding are given in Figs. 74, 75, which, for clearness, have been drawn with only one turn per coil.

The connections shown in these diagrams are representative of those which would be adopted when pole-changing is not required. To obtain a pole-changing winding it will be necessary to bring out leads from a large number of coils, so that the connections of either Fig. 74 or Fig. 75 may be obtained as desired. An examination of these diagrams will show that 48 leads are necessary to obtain eight poles, and 24 additional leads are necessary to obtain six poles. Hence ($48 + 24 =$) 72 leads will be required for the pole-changing winding, the disposition of the leads being shown in Fig. 76. If these leads are to be inter-connected exactly in the manner shown in Figs. 74, 75, then, obviously, 72 external cables will be required between the motor and the pole-changing switch. But

* Details of the mechanical and electrical equipment of these locomotives are given in the *Rivista Tecnica delle ferrovie italiane*, vol. 10, p. 213. See also *Tramway and Railway World*, vol. 42, p. 387.

† Particulars of the equipment of these locomotives are given in the *Electric Journal*, vol. 12, p. 51



FIGS. 74, 75.—Connections and Development of Three-phase, Whole-coiled Windings for 8 Poles and 6 Poles.

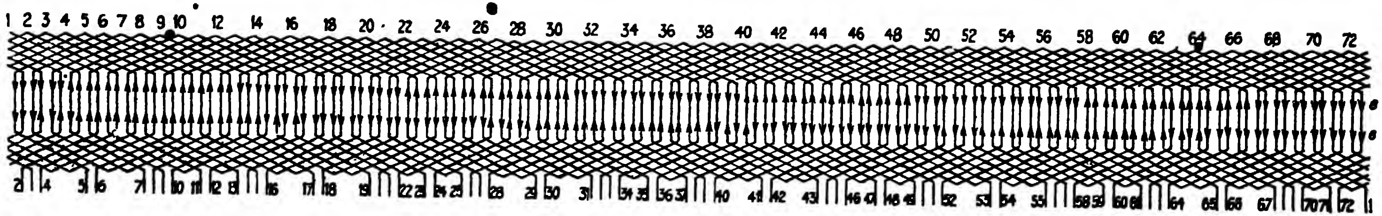


FIG. 76.—Showing the disposition of the Coil Leads to obtain a Pole-changing Winding for 8 and 6 Poles.

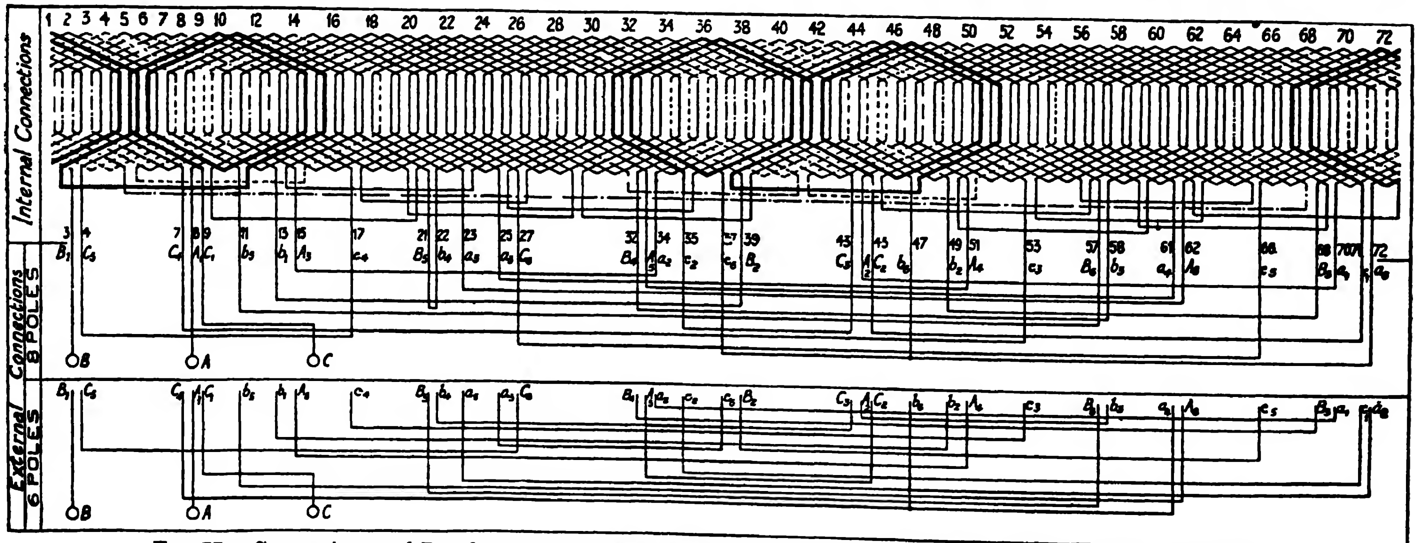


FIG. 77.—Connections and Development of Three-phase, Whole-coiled, Pole-changing Winding for 8 and 6 Poles.

by adopting a different scheme for the inter-connections, the number of external cables between motor and pole-changing switch may be reduced to 36. It will be of interest to show how this result is obtained.*

First it is necessary to determine, from Figs. 74, 75, the direction of current in each coil which gives the correct polarities. We select, therefore, a given instant in the cycle, ascertain the directions of the line currents, and mark these directions on the slot portion of the conductors. In Fig. 76 the upper row of arrow-heads shows the directions of the currents to give eight poles, while the lower row of arrow-heads shows the directions to give six poles; the instant selected corresponding to the currents in phases *A* and *C* having a positive direction (which is assumed to be *towards* the neutral point of the motor circuit) and the current in phase *B* having a negative direction.

Next prepare a table giving, for each set of poles, the phase positions of all the coils and the directions of current in the coils, thus—

Number of Coil (see Fig. 76).	Designation of Coil Leads.	Phase Position.		Direction of Current in Coil.*		Number of Coil (see Fig. 76).	Designation of Coil Leads.	Phase Position.		Direction of Current in Coil.*	
		8 Poles.	6 Poles.	8 Poles.	6 Poles.			8 Poles.	6 Poles.	8 Poles.	6 Poles.
2	1, 4	*C*	*B*	CCW	CCW	*38*	37, 40	*C*	*B*	CCW	CW
3, 4, 5	3, 6	*B*	*B*	CCW	CCW	*39, 40, 41*	39, 42	*B*	*B*	CCW	CW
6, 7, 8	5, 8	*A*	*A*	CCW	CCW	*42, 43, 44*	41, 44	*A*	*A*	CCW	CW
9	7, 10	*C*	*A*	CW	CCW	*45*	43, 46	*C*	*A*	CW	CW
10, 11	9, 12	*C*	*C*	CW	CW	*46, 47*	45, 48	*C*	*C*	CW	CCW
12, 13	11, 14	*B*	*C*	CW	CW	*48, 49*	47, 50	*B*	*C*	CW	CCW
14	13, 16	*B*	*B*	CW	CW	*50*	49, 52	*B*	*B*	CW	CCW
15, 16, 17	15, 18	*A*	*B*	CW	CW	*51, 52, 53*	51, 54	*A*	*B*	CW	CCW
18, 19, 20	17, 20	*C*	*A*	CCW	CW	*54, 55, 56*	53, 56	*C*	*A*	CCW	CCW
21	19, 22	*B*	*A*	CCW	CW	*57*	55, 58	*B*	*A*	CCW	CCW
22, 23	21, 24	*B*	*C*	CCW	CCW	*58, 59*	57, 60	*B*	*C*	CCW	CW
24, 25	23, 26	*A*	*C*	CCW	CCW	*60, 61*	59, 62	*A*	*C*	CCW	CW
26	25, 28	*A*	*B*	CCW	CCW	*62*	61, 64	*A*	*B*	CCW	CW
27, 28, 29	27, 30	*C*	*B*	CW	CCW	*63, 64, 65*	63, 66	*C*	*B*	CW	CW
30, 31, 32	29, 32	*B*	*A*	CW	CCW	*66, 67, 68*	65, 68	*B*	*A*	CW	CW
33	31, 34	*A*	*A*	CW	CCW	*69*	67, 70	*A*	*A*	CW	CW
34, 35	33, 36	*A*	*C*	CW	CW	*70, 71*	69, 72	*A*	*C*	CW	CCW
36, 37	35, 38	*C*	*C*	CCW	CW	*72, 1*	71, 2	*C*	*C*	CCW	CCW

* CCW denotes counter-clockwise; CW denotes clockwise.

An analysis of this table will show that certain coils are common to a given phase for each combination of the winding, while other coils have to be changed from one phase to another when the number of poles is changed. Moreover, with certain coils, the direction of current is the same for both sets of poles, but, with other coils, the direction

* The scheme of interconnections given here has been worked out by the author and was first published in his *Electric Motors and Control Systems*. The diagrams (Figs. 74–77) and tables were prepared specially for that volume.

of current must be reversed when the number of poles is changed. The analysis may be summarized thus—

(*a*) Coils which are common to a given phase, and in which the direction of current is the same for both sets of poles—

6, 7, 8, 69 (phase A); 3, 4, 5, 14 (phase B); 10, 11, 72, 1 (phase C).

(*b*) Coils which are common to a given phase, and in which the direction of current must be reversed when the number of poles is changed—

33, 42, 43, 44 (phase A); 39, 40, 41, 50 (phase B); 36, 37, 46, 47 (phase C).

(*c*) Coils which have to be changed in phase *without* reversal of current—

15, 16, 17, 26 (A to B); 24, 25, 34, 35 (A to C);
57, 66, 67, 68 (B to A); 12, 13, 22, 23 (B to C);
45, 54, 55, 56 (C to A); 2, 63, 64, 65 (C to B).

(*d*) Coils which have to be changed in phase *with* reversal of current—

51, 52, 53, 62 (A to B); 60, 61, 70, 71 (A to C);
21, 30, 31, 32 (B to A); 48, 49, 58, 59 (B to C);
9, 18, 19, 20 (C to A); 27, 28, 29, 38 (C to B).

The four coils in each of above sets may, therefore, be connected permanently in series. But each set of (four) coils consists of two groups, of which one group contains either a single coil or two adjacent coils connected in series, and the other group contains either three or two coils connected in series. Now each group of one, two, or three coils corresponds to two coil leads (see Fig. 76); hence, after the above series connections have been made, we shall have only 36 leads remaining. The interconnections between these leads must be made by the pole-changing switch.

The **complete connections of the winding** for both sets of poles are shown in Fig. 77. In this diagram the 36 external leads have been marked according to the phase position occupied by the coils, to which the leads belong, when the winding is connected for eight poles. For example, the external leads, Nos. 8 and 70 (Figs. 76, 77), belonging to the set of (four) coils Nos. 6, 7, 8, 69, are marked A_1, a_1; the leads Nos. 3 and 16 belonging to the set of (four) coils Nos. 3, 4, 5, 14 are marked B_1, b_1; the leads Nos. 9 and 71 belonging to the set of coils Nos. 10, 11, 72, 1 are marked C_1, c_1. The leads of the other sets of coils have been marked in like manner. The leads from the six groups of coils forming one phase will, therefore, be marked as follows— A_1, a_1; A_2, a_2; A_3, a_3; A_4, a_4; A_5, a_5; A_6, a_6; and the leads for the B and C phases will be marked similarly.

To obtain eight poles, connections are made between the leads as follows—

Phase A.—a_1–A_2; a_2–A_3; a_3–A_4; a_4–A_5; a_5–A_6.
Phase B.—b_1–B_2; b_2–B_3; b_3–B_4; b_4–B_5; b_5–B_6.
Phase C.—c_1–C_2; c_2–C_3; c_3–C_4; c_4–C_5; c_5–C_6.
Neutral point, a_6–b_6–c_6. Lines on A_1, B_1, C_1.

To obtain six poles certain groups of coils must be interchanged between phases and reversed in accordance with the scheme given on

p. 131. The connections to be made between the external leads are as follows—

Phase A.—a_1–a_2 ; A_2–b_3 ; B_3–B_4 ; b_4–C_3 ; c_3–c_4.
Phase B.—b_1–b_2 ; B_2–c_5 ; C_5–C_6 ; c_6–a_3 ; A_3–A_4.
Phase C.—c_1–c_2 ; C_2–A_5 ; a_5–a_6; A_6–b_5 ; B_5–B_6.
Neutral point, a_4–b_6–C_4. Lines on A_1, B_1, C_1.

Let us now ascertain the relative flux-densities corresponding to the two sets of poles. If we assume a total of 144 slots—i.e. 6 slots per pole per phase for eight poles, and 8 slots per pole per phase for six poles—the breadth coefficients for the 8-pole and 6-pole combinations of the winding have approximately the same value, viz. 0·956. The differential factors are 1·0 and 0·924 respectively. Hence, assuming equal line voltages (V) in the two cases and neglecting the internal voltage drop, the fluxes per pole are—

$$\Phi_8 = V/(0{\cdot}956Nf)\,; \quad \Phi_6 = V/(0{\cdot}956 \times 0{\cdot}924Nf)$$

Whence $\Phi_6 = 1{\cdot}08\Phi_8$.

Therefore the flux-density in the stator and rotor cores, back of the clots, is increased 8 per cent when the number of poles is changed from eight to six. But, for the smaller number of poles, the flux-density in the air-gap is only 81 per cent of that corresponding to the larger number of poles. Hence approximately equal outputs are obtained for both 6-pole and 8-pole operation.

The **rotor winding** may be of the same type as the stator winding and may be connected in the same manner, but the pole-changing switch must be arranged internally so that only three slip-rings are required. This switch, as well as that for the stator winding, may be operated pneumatically. Alternatively, the special two-three-phase single rotor winding described on p. 133 may be employed, in which case no pole-changing switch is required for the rotor.

We have now to consider whether or not two of these motors can be operated in cascade. With high-voltage motors having three-phase pole-changing rotor windings, it may be impracticable to re-group the pole-changing stator winding of the secondary motor so as to be suitable for the rotor voltage (at cascade synchronous speed) of the primary motor. Under these conditions cascade operation will be only possible if the *rotor* of the secondary motor is supplied from the rotor of the primary motor, and the rheostat is connected to the stator of the secondary motor. This method of operation requires special features in the rheostat, which are discussed in Chapter XI.

Cascade operation of motors having the above three-phase pole-changing stator winding and the special two-three-phase single rotor winding of Fig. 80, is obviously only possible by supplying the rotor of the secondary motor from the rotor of the primary motor.

We will now discuss the **alternative method of obtaining eight and six poles from a single pole-changing winding.** This method, which is applicable to single-layer windings, involves a change in the number of phases when the number of poles is changed. For example, when the number of poles is changed from eight to six, the number of phases must be changed from three to two.

The necessity for changing the number of phases, when changing

the number of poles, will be apparent from an examination of a diagram of a three-phase, 8-pole, half-coiled, single-layer, spiral winding with full-pitch coils. It will be found that although a 6-pole, *three-phase* winding is impossible, a symmetrical 6-pole, *two-phase* (75 per cent pitch) winding is quite practicable and involves only a change in the connections between the groups of coils. Thus, for a 24-slot wave winding, the connections for eight poles, three phases, are*—

Phase I.	1‾4_7‾10_13‾16_19‾22
Phase II.	3‾6_9‾12_15‾18_21‾24
Phase III.	5‾8_11‾14_17‾20_23‾2

and the connections for six poles, two phases, are—

Phase I. . .	3‾6_10‾7_11‾14_18‾15_19‾22_2‾23
Phase II. . .	1‾4_8‾5_9‾12_16‾13_17‾20_24‾21

Diagrams showing the connections of this winding—which is suitable for the stator—are given in Fig. 78, and the relative positions of the coils and end connections for a two-range winding are shown in Fig. 79. These diagrams show also the phase relations of the coils for the three-phase and two-phase connections. It will be observed that the winding is *half-coiled* when connected for three phases, and *whole-coiled* when connected for two phases. The two-phase winding may be supplied from the three-phase system by means of two "T-connected" auto-transformers, as described in Chapter XI (p. 298).

Let us now turn our attention to the **rotor winding**. Obviously this must be suitable for either six or eight poles. Since cascade working is to be adopted, the rotor winding must be capable of supplying both three-phase and two-phase current, viz. three-phase current with eight poles, and two-phase current with six poles. Although these requirements may appear to be rather onerous for a single winding, nevertheless a single winding can be arranged to fulfil them. Thus, instead of the usual star-connected three-phase rotor winding generally adopted, we may use four star-connected three-phase windings connected permanently in parallel. This winding is wound with the same number of conductors as the usual winding, and the three common ends are connected to one set of three slip-rings, while the four neutral points are connected to another set of four slip-rings.

A diagram showing the application of this principle to a 24-slot single-layer winding is given in Fig. 80, and a schematic diagram of the circuits is given in Fig. 81. The winding consists of twelve coils, hence each phase of the four three-phase circuits contains one coil. Now the angular spacing of the coils in the diagram is $(\frac{1}{12} \times 2\pi =) \frac{1}{6}\pi$ radians, or 30°, which corresponds to a phase difference of $(\frac{1}{12} \times 8\pi) = \frac{2}{3}\pi$ radians, or 120°, in an 8-pole field, and $(\frac{1}{12} \times 6\pi =) \frac{1}{2}\pi$ radians, or 90°, in a 6-pole field. Hence coils in the diagram which have an angular spacing of 120° will have a phase difference of $(4 \times \frac{2}{3}\pi =) 2\frac{2}{3}\pi$ radians—equivalent to 120 electrical degrees—in an 8-pole field and $(4 \times \frac{1}{2}\pi =) 2\pi$ radians—equivalent to zero electrical degrees—in a 6-pole field. Therefore, a three-phase winding for an 8-pole field may be formed from any three

* The scheme of connections given here, for stator and rotor windings, was originally worked out by the author for the first edition of *Electric Traction*, but only the winding diagrams were presented. In the present edition the methods by which the windings were obtained are given in detail.

coils for which the angular spacing is 120°: and, as there are 12 coils, four similar three-phase windings will be obtained. Obviously these windings may be permanently connected in parallel.

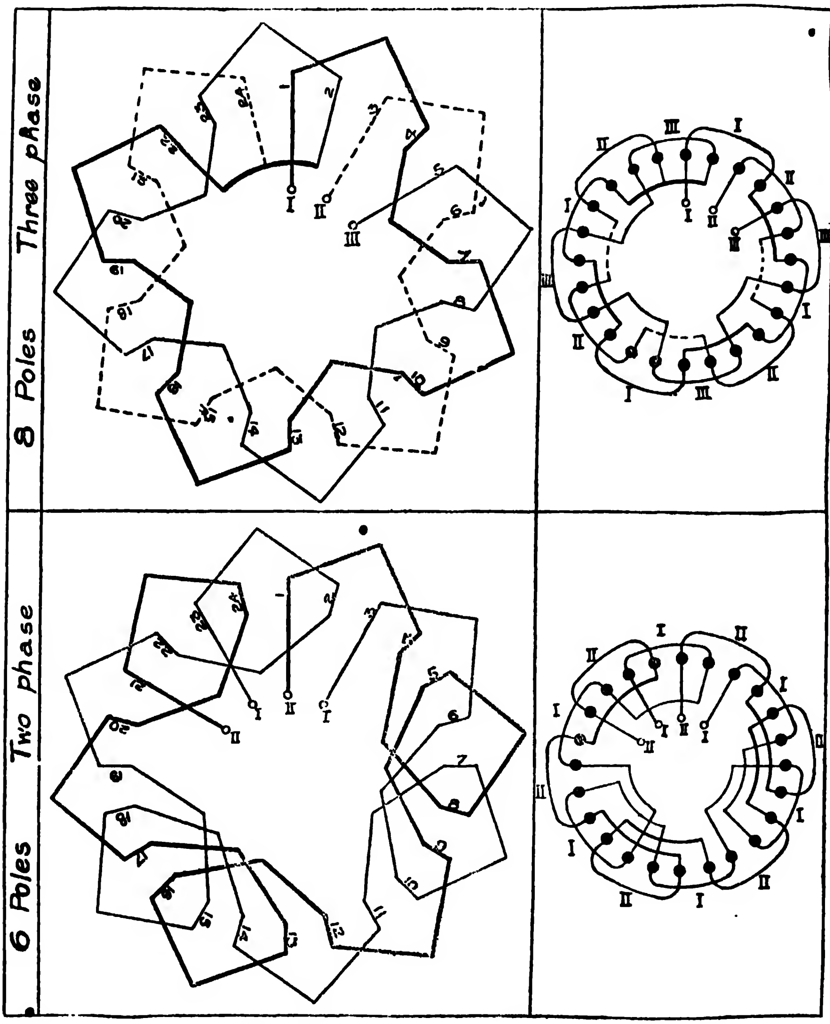


Fig. 78. Fig. 79.
Connections of Single-layer Pole-changing Winding to give 8 Poles, Three-phase, and 6 Poles, Two-phase.

The scheme of connections (see Fig. 80) is as follows—

Phase A_1.	Ring E—4–1—	Ring A.	Phase A_2.	Ring E—10–7—	Ring D.
Phase B_1.	Ring F—12–9		Phase B_2.	Ring F—18–15—	
Phase C_1.	Ring G—20–17—		Phase C_2.	Ring G—2–23—	
Phase A_3.	Ring E—16–13—	Ring B.	Phase A_4.	Ring E—22–19—	Ring C.
Phase B_3.	Ring F—24–21—		Phase B_4.	Ring F—6–3—	
Phase C_3.	Ring G—8–5—		Phase C_4.	Ring G—14–11—	

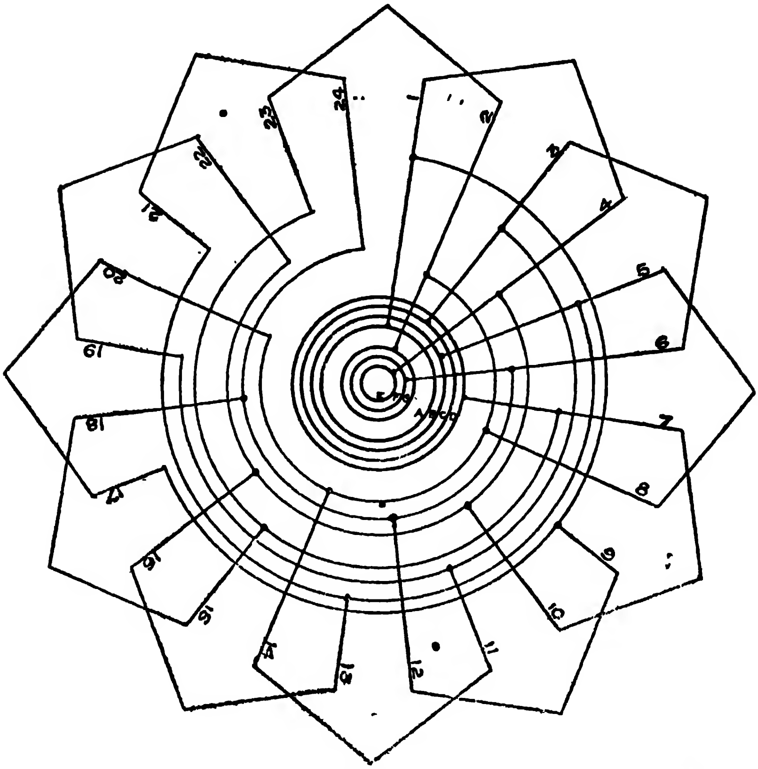


FIG. 80.—Connections of Rotor Winding suitable for the Pole-changing Stator Winding of Fig. 78.

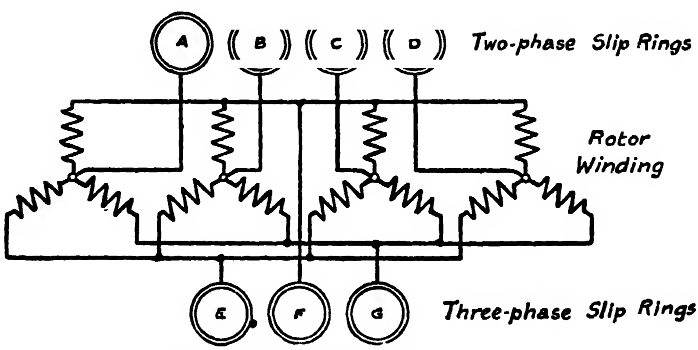


FIG. 81.—Diagram of Circuits for the Winding shown in Fig. 80.

Now if these windings are placed in a 6-pole field, the E.M.Fs. induced in the three phases of any given winding will be in phase, while the E.M.Fs. induced in corresponding phases of the four circuits will have a phase difference of 90°. For example, the phase difference of the

E.M.Fs. induced in phases A_1 and A_2 is $(3 \times \frac{1}{2}\pi =)$ $1\frac{1}{2}\pi$ radians—equivalent to 270°—while the values for the remaining circuits are—

Phases A_1 and A_3—$(6 \times \frac{1}{2}\pi =)$ 3π radians = 180 degrees;
Phases A_1 and A_4—$(9 \times \frac{1}{2}\pi =)$ $4\frac{1}{2}\pi$ radians = 90 degrees;
Phases A_2 and A_4—$(6 \times \frac{1}{2}\pi =)$ 3π radians = 180 degrees.

Hence the corresponding phases of the four three-phase, 8-pole, windings form the (four) phases of a star-connected four-phase winding, so that, with a 6-pole field, the rotor winding is equivalent to three four-phase star-connected windings in parallel. The circuits (see Fig. 80) are as follows—

Phase W_1....Ring A—1-4—		Phase W_2....Ring A—9-12—
Phase X_1....Ring C—19-22—	Ring E.	Phase X_2....Ring C—3-6—
Phase Y_1....Ring B—13-16—		Phase Y_2....Ring B—21-24—
Phase Z_1....Ring D—7-10—		Phase Z_2....Ring D—15-18—

Ring F (for Phases W_2, X_2, Y_2, Z_2).

Phase W_3....Ring A—17-2—
Phase X_3....Ring C—11-14— Ring G.
Phase Y_3....Ring B—5-8—
Phase Z_3....Ring D—23-2—

The three neutral points of these windings, however, cannot be interconnected, as this would prevent the winding being used in the 8-pole field.

Four E.M.Fs., or currents, differing 90° in phase may be obtained from the following pairs of slip-rings: A–C, C–B, B–D, D–A, while two E.M.Fs., or currents, differing 90° in phase, may be obtained from slip-rings A–B, C–D.

Thus, in a 6-pole field, the rotor can supply either two-phase or four-phase current, and, in an 8-pole field, it can supply three-phase current.

The voltage relations will now be investigated. Let $3N$ denote the total number of turns in the stator winding, and Φ_3, Φ_2 denote respectively the fluxes corresponding to a terminal voltage V in each case. Then the turns in series per phase will be N for the three-phase 8-pole connection, and $3N/2$ for the two-phase 6-pole connection. If the breadth coefficients for the 8-pole and the 6 pole windings be assumed as 0·96 and 0·9 respectively, then we must have

$$V/\sqrt{3} = 4{\cdot}44 \times 0{\cdot}96\Phi_3 Nf \times 10^{-2},$$

and $$V = 4{\cdot}44 \times 0{\cdot}9 \times 0{\cdot}92\Phi_2\, 3N/2f \times 10^{-2}.$$

whence $$\Phi_2 = 1{\cdot}34\Phi_3.$$

For equal fluxes in two-phase and three-phase working the terminal voltage for the 6-pole winding must therefore be 0·75 of the normal three-phase line voltage. This voltage can readily be obtained from the auto-transformer.

Let N' denote the total number of turns in the rotor winding; then there are $\frac{1}{12}N'$ turns in series per phase for three-phase working, and $\frac{1}{6}N'$ turns in series per phase for two-phase working. Hence, with equal fluxes (Φ), and assuming the same breadth coefficients as above, the voltage (V_3) between the three-phase slip-rings is

$$V_3 = \sqrt{3} \times 4{\cdot}44 \times 0{\cdot}96 \times \Phi \times \tfrac{1}{12}N' \times f \times 10^{-2},$$

and the voltage (V_2) between the two-phase slip-rings is

$$V_2 = 4{\cdot}44 \times 0{\cdot}9 \times 0{\cdot}92 \times \Phi \times \tfrac{1}{6}N' \times f \times 10^{-2},$$

whence $V_2 = V_3$. Thus cascade working will be practicable for both sets of poles.

General Considerations Relating to Three-Phase Traction Motors

The principal considerations—other than those for obtaining speed variation—in the design of three-phase motors for traction service are : (1) number of poles, (2) leakage factor, (3) air-gap, (4) ventilation (as affecting the temperature rise).

The selection of the **number of poles** involves considerations of power-factor and operating speeds. To obtain a high power-factor the smallest

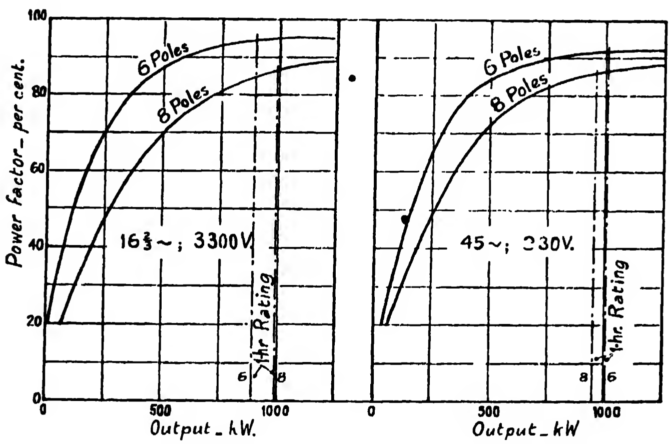


Fig. 82.—Power-factor Curves of Brown-Boveri 1000 kW. Motors.

practicable number of poles should be chosen consistent with low leakage reactances for the windings. For example, with large, 1000 h.p., motors six poles is the minimum, and with a low frequency (16⅔ cycles) a gearless drive is practicable. But with industrial frequencies (40 to 50 cycles) and six poles a geared drive is necessary owing to the relatively high synchronous speed of the motor. The use of gearing in this case is preferable to a gearless drive and the increase of the minimum number of poles to 12 or 16, as the latter would reduce seriously the power-factor, and would result in exceptionally low power-factors when lower speeds were obtained by pole-changing and cascading. The manner in which the number of poles affects the power-factor of large motors is shown by the curves of Fig. 82.

The **leakage factor** is an important feature in the design, as it affects both the maximum power-factor and the overload capacity. This factor (σ) is usually defined as the ratio of the magnetizing current to the ideal short-circuit current (at normal voltage). Its relationship to the

maximum power-factor and overload capacity can be determined from the circle diagram, and is given by

$$\text{Maximum power-factor} = (1 - \sigma)/(1 + \sigma)$$
$$\text{Overload capacity} = (1 + \sigma)/2\sqrt{\sigma}$$

Practical requirements, therefore, necessitate a low value for σ, i.e. a relatively small magnetizing current and a large ideal short-circuit current.*

The **air-gap** of a three-phase traction motor is generally larger than that of a stationary motor of similar size. To obtain a high power-factor under these conditions a low frequency of supply is essential, together with few poles, nearly closed slots, and end connections of low leakage reactance. With large Continental motors for locomotives, the air-gap is of the order of 2 mm. (0·08 in.), which is about 60 per cent larger than the air-gap adopted for a stationary three-phase motor of similar output. However, the air-gap of 0·08 in. is very small in comparison with the air-gap of direct-current railway motors (which is of the order of 0·18 to 0·25 in.). The bearings of three-phase motors must, therefore, be designed more liberally than those of direct-current traction motors, and an efficient system of lubrication must be adopted.

The **natural ventilation** of polyphase traction motors is generally better than that of direct-current open-type motors, owing to the more open construction of the rotor core and spider. Moreover, the absence of a commutator and exposed live parts, enables the end shields to be of an open design, so that free circulation of air can occur through the motor.

The largest portion of the total losses usually occurs in the stator, and comprises the stator core loss and the I^2R loss in the stator winding. The stator frame is, therefore, designed to secure a large radiating surface, and is either of a box section with ventilating apertures, or of a thin, solid section with radiating fins. The losses in the stator are, therefore, readily dissipated, and with an open design for the end shields the motor will attain its final temperature after a comparatively short run of from two to three hours.

Rating.—The method of rating must obviously depend upon the class of service on which the motor is to operate, and where this service involves long-distance runs and regenerative braking the motors must be rated on a continuous basis.

Examples of Three-phase Traction Motors

Three-phase traction motors are usually built for locomotive service and are frame-mounted machines of large output, the power being transmitted from the motors to a number of coupled driving wheels by cranks and connecting rods. Owing to the constant-speed characteristic of the motors, a distributed, or individual-axle, drive—as employed with direct-current and single-phase locomotives—is undesirable, as slight differences in the diameters of the driving wheels would cause unequal loading of the motors (see p. 42). Hence the collective drive with two motors and

* For the calculation of these quantities, see *Papers on Alternating-Current Machinery*, Hawkins, Smith, and Neville (Pitman).

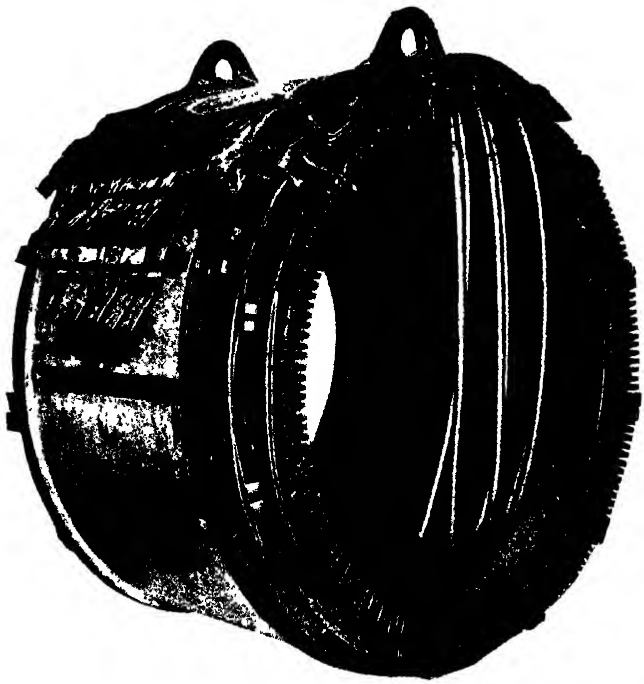


FIG. 83.—Stator of Westinghouse 410 h.p., 8/4 Poles, 25 Cycles, Three-phase Railway Motor.

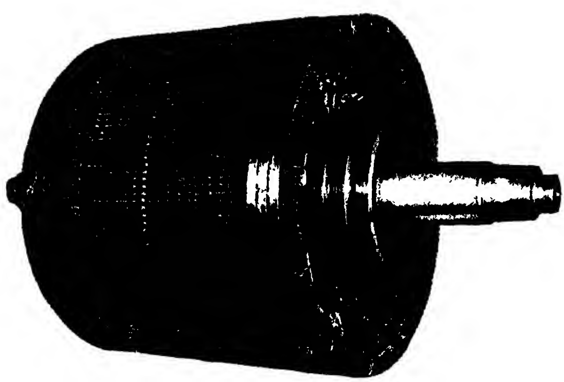


FIG. 84.—Rotor of Westinghouse 410 h.p., 8/4 Poles, 25 Cycles, Three-phase Railway Motor.

mechanical coupling of the rotor shafts and driving axles is the preferred arrangement in practice.

In cases where gearing must be employed—e.g. when exceptionally low operating speeds are required or when the supply frequency is of the order of 40 or 50 cycles—the gear wheels and driving cranks are mounted

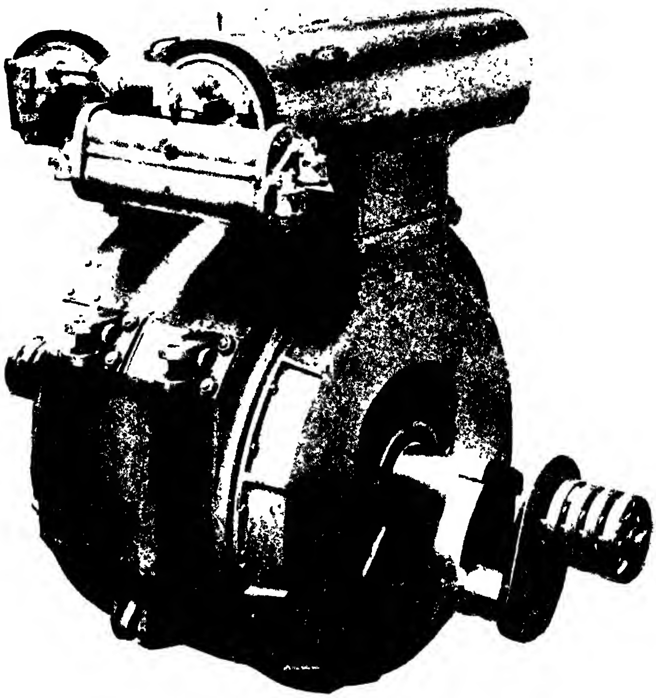


FIG. 85.—Societa Italiana Westinghouse 1300 h.p., 8/6 poles, $16\frac{2}{3}$ cycles, Three-phase Railway Motor. NOTE.—This motor forms the secondary motor for cascade working. The pole-changing, re-grouping, and change-over switches are mounted on the frame of the motor, and are operated electro-pneumatically.

on intermediate shafts (called " jack shafts ") which are carried in suitable bearings in the locomotive frame.

The largest application of three-phase motors to railway traction is in Italy. The low-frequency system ($16\frac{2}{3}$ cycles) is employed extensively in Northern Italy, but the normal-frequency system (45 cycles) is being adopted for electrification in Central Italy. Over 250 locomotives are in service, the electrical equipment of which was supplied jointly by the Società Italiana Westinghouse and the Tecnomasio Italiano Brown-Boveri.

Three-phase traction motors have also been built by the Westinghouse Co. for the heavy split-phase locomotives of the Norfolk and Western Railway and the Pennsylvania Railroad.

Views of the stator and rotor of a geared motor for the Norfolk and Western locomotives are given in Figs. 83, 84. The construction of

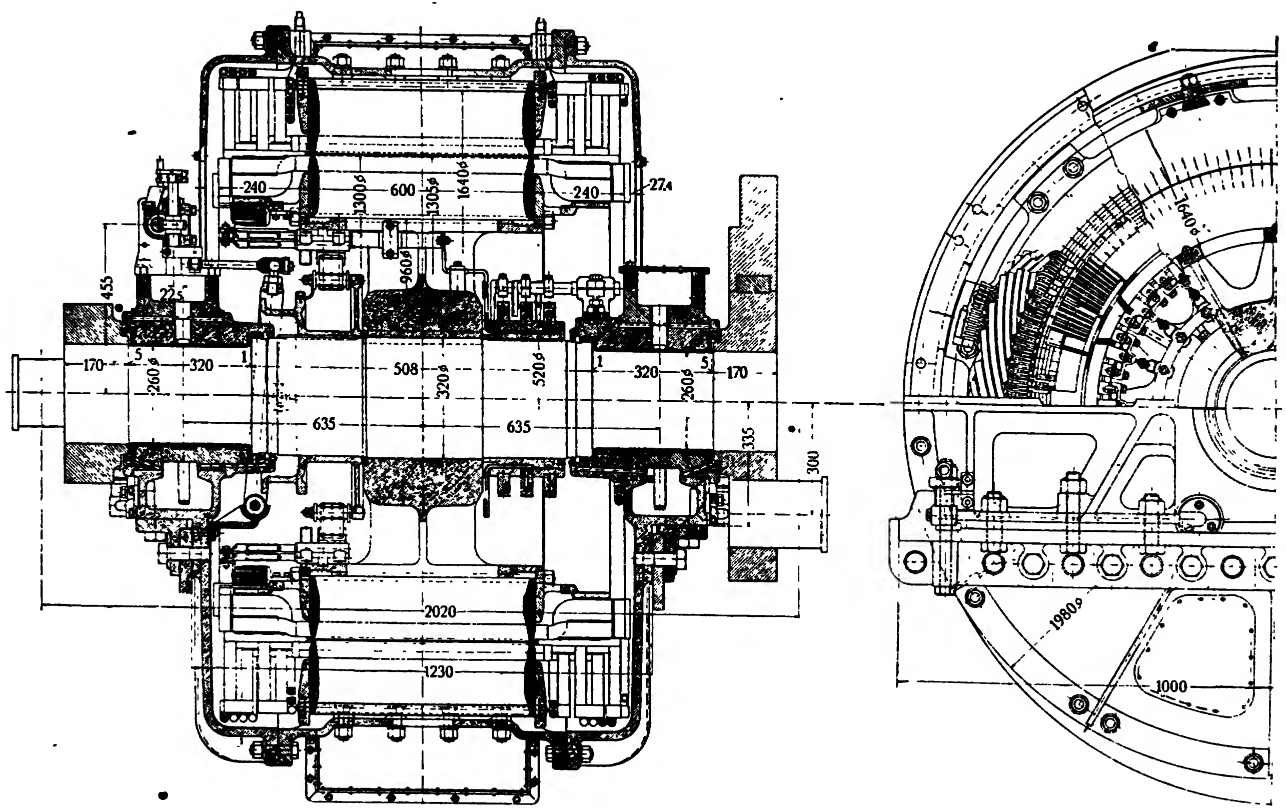


FIG. 86.—Longitudinal and Cross-sections of Brown-Boveri Gearless Locomotive Motor.

the stator core should be noted; the punchings are riveted to steel end-rings, which are furnished with eye bolts, and are seated in a half-frame forming part of the truck. The upper portion of the motor is enclosed in a pressed steel frame which communicates with the ventilating duct on the locomotive.

Fig. 85 shows a typical **gearless motor** (Società Italiana Westinghouse) for passenger locomotive service on the Italian State Railways. This motor is designed for combined pole-changing and cascade control, the poles being changed in the ratio of 1·33 : 1 (i.e. 8 : 6) according to the

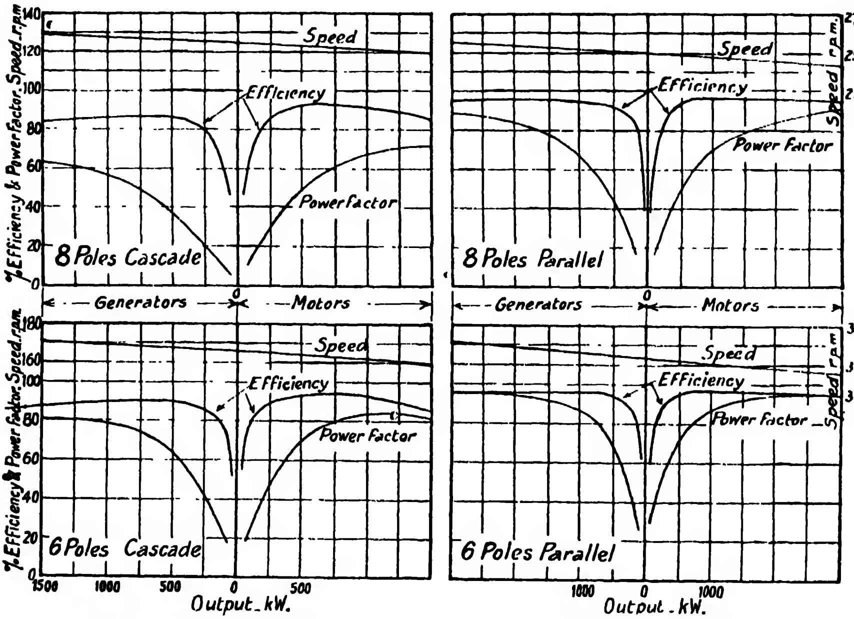


FIG. 87.—Performance Curves of Brown-Boveri three-phase, 3300 volt, 16⅔-cycle, four-speed Locomotive Motors.

method shown in Fig. 78. The switches for performing the functions of pole-changing, re-grouping the stator windings (for cascade working), and interconnecting the motors (for cascade working), are located on the motor frame and are operated electro-pneumatically. The two sets of slip-rings can be seen in the illustration.

Fig. 86 shows longitudinal and cross-sections of another gearless passenger locomotive motor (Tecnomasio Italiano Brown-Boveri) in service on the Italian State Railways. This motor is also designed for combined pole-changing and cascade control. The stator and rotor windings are arranged to give either eight or six poles and to be suitable for a three-phase supply in both cases. Hence the scheme of connections must be in accordance with Fig. 77, and pole-changing switches will be required for both stator and rotor windings. The pole-changing switch for the rotor winding is located in the interior of the rotor and is operated pneumatically. Therefore only three slip-rings are necessary: they are mounted on the shaft as shown in Fig. 86.

This motor is designed for the full line voltage (3300 volts), and its weight without cranks and balance weights is approximately 14 tons. It has a one-hour rating of 1300 h.p. when connected for eight poles.

Fig. 87 shows the performance curves for a pair of these motors (i.e. the power equipment of one locomotive) for cascade and parallel

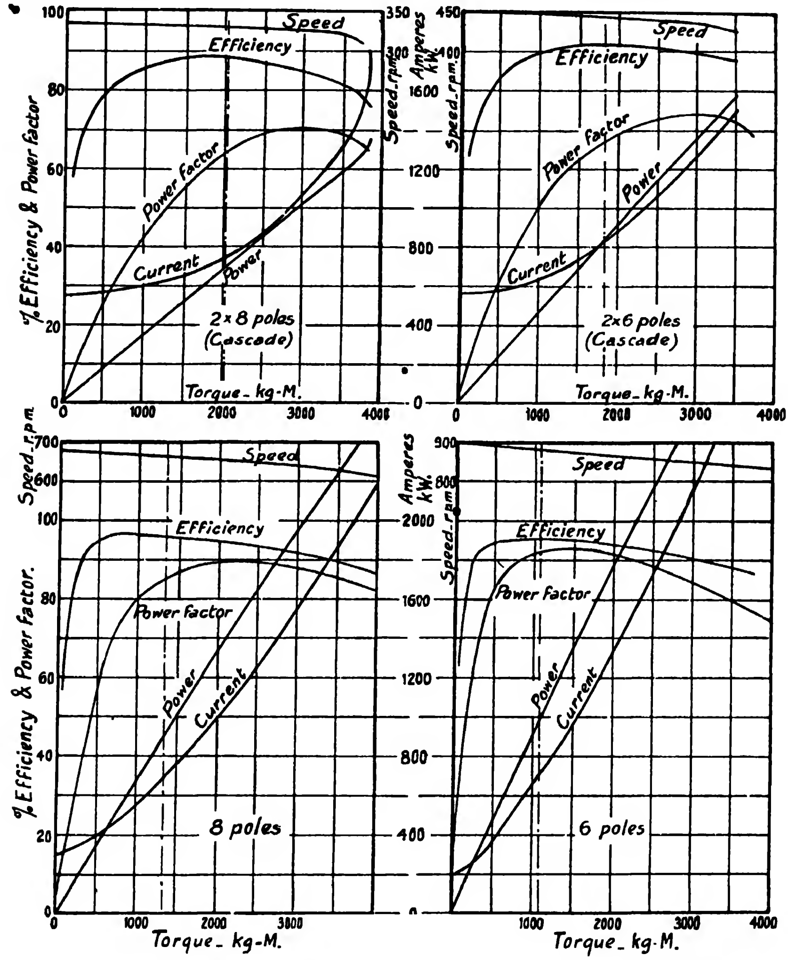


FIG. 88.—Performance Curves of Brown-Boveri three-phase, 930 volt, 45 cycle, 6/8 pole, Locomotive Motor.

[NOTE.—The upper set of curves show the performance of the motor when cascaded with a similar motor. The chain dotted ordinates indicate the 1-hour load in each case.]

operation with both sets of poles. Curves are also given showing the performance of these machines when operating as induction generators—i.e. when used for regenerative braking. The high efficiency for both motor and generator operation should be noted.

Fig. 88 shows the performance curves of a motor of similar output, but designed for a frequency of 45 cycles instead of $16\frac{2}{3}$ cycles, this

motor forming part of the equipment of locomotives built by the Tecnomasio Italiano Brown-Boveri for the Tivoli-Rome section of the Italian State Railways, which operates at 10,000 volts, 45 cycles. The motors are designed for combined pole-changing and cascade control. The three-phase stator windings are arranged to give either eight or six poles, according to the scheme of Fig. 77, and the rotor winding follows the scheme shown in Fig. 80. Owing to the relatively small numbers of

FIG. 89.—Rotor of Brown-Boveri Four-speed, Three-phase Railway Motor.

poles—which were adopted from considerations of power-factor—the synchronous speeds are high, and, in consequence, gearing has had to be employed in the power transmission.

The performance curves show that a maximum power-factor of 92 per cent and a maximum efficiency of nearly 96 per cent (which, however, does not include losses in the gearing) is obtained with these motors.

Four-speed changeable-pole motors with squirrel-cage rotors have been developed by Brown, Boveri & Co. for three-phase locomotives, examples of which are in operation through the Simplon Tunnel and on the Burgdorf-Thun Railway. The motors have two stator windings (wound with poles in the ratio of 1·5 : 1), and each winding is arranged so that the poles may be changed in the ratio of 2 : 1. Therefore the four synchronous speeds are in the ratio 1 : 1·5 : 2 : 3.

The use, for traction purposes, of a motor with a squirrel-cage rotor calls for a number of special features in the rotor in order that sufficient starting torque may be obtained without excessive currents in the stator and without large losses occurring at normal load.

It is apparent that if the squirrel-cage rotor were designed with a

moderately low resistance suitable for normal running conditions, then means must be adopted to increase, temporarily, this resistance at starting.* Moreover, since practically the whole of the losses during starting occur in the rotor, the ventilation of this part of the motor must be given special attention.

The manner in which these problems have been solved by Messrs. Brown-Boveri is shown in the following details.

A view of a typical rotor is shown in Fig. 89. The conductors consist of bare copper tubes, and are placed directly in the slots, so that the

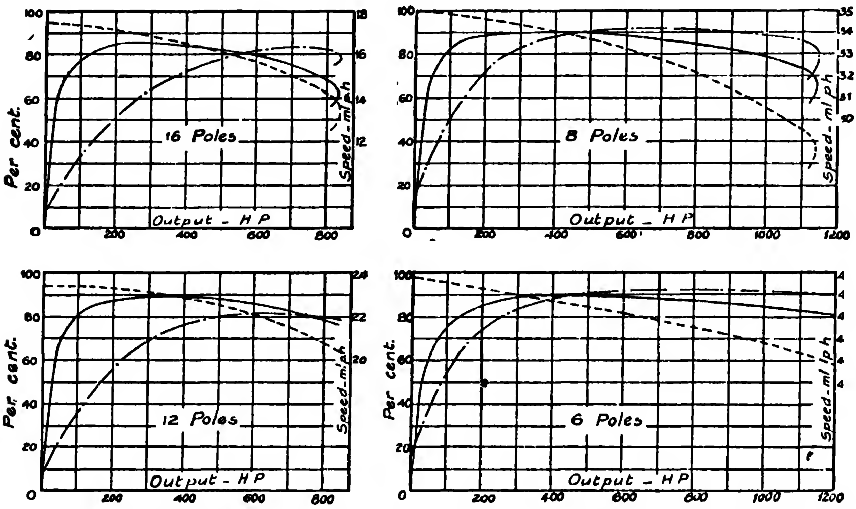


FIG. 90.—Characteristic Curves of Brown-Boveri Four-speed, Three-phase Railway Motor (3000 volts, 16 Cycles; wheels, 1250 mm.—49·2 in.-diameter). NOTE.—Full lines denote efficiency, chain-dotted lines denote power-factor.

tubes are in contact with the rotor laminations. The ends of the tubes are connected together with thin strips of copper, which are arranged radially between the conductors and the short-circuiting rings, the latter being fixed to the shaft. Thus a large radiating surface is obtained, and, at the same time, the end connections act as fans and produce an efficient circulation of air through the motor. The end connections are designed to have, normally, a resistance considerably greater than that of the rotor conductors, and the joints between the various portions of the rotor winding are made to withstand satisfactorily a temperature of 250° C. This type of construction is very robust, and the results obtained on the locomotives operating through the Simplon Tunnel have been very satisfactory.

* A high apparent resistance (and a low reactance) at starting may be obtained by the use of rotor conductors of small width and great depth. In this case the increased apparent resistance is due to the "skin effect." The disadvantage of the method, however, is that the motor will have a lower overload capacity than one of normal design.

This method and its influence on the performance of the motor are discussed in Hobart's *Design of Polyphase Generators and Motors*, p. 168.

During the first few seconds in starting from standstill, the rotor current is of such magnitude that the temperature of the end connections reaches about 200° C. The resistance of the rotor winding at this temperature is about 50 per cent higher than the resistance corresponding

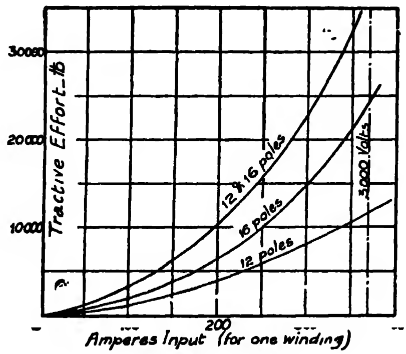


Fig. 91.—Starting Performance of Brown-Boveri, Four-speed, Three-phase Railway Motor.

to normal load and about 80 per cent higher than the cold resistance. Thus the above conditions are satisfied.

The exceptionally good ventilation and the large cooling surfaces result in the temperature of the rotor winding becoming normal as soon as full speed is attained.

The efficiency, power-factor, and speed curves of a typical motor are given in Fig. 90, while curves of the starting torque are given in Fig. 91. These curves show the advantage of the larger number of poles at starting, and also the effect of connecting the two stator windings in parallel.

CHAPTER VII

THE TESTING OF TRACTION MOTORS

Introduction. Tests on traction motors may be divided into two classes, viz. (1) factory tests, which include (*a*) commercial tests run on standard machines, (*b*) special tests applied to machines of a new design; and (2) tests in service, which are generally of a special nature, and are run to ascertain if a motor equipment fulfils the guaranteed conditions of service.

It will be convenient to discuss first the factory tests applied to direct- and alternating-current motors, and to follow this with a discussion of representative tests in service.

PART I

FACTORY TESTS ON DIRECT-CURRENT TRACTION MOTORS

The A.I.E.E. Standards and B.E.S.A. Specification for traction motors define (excerpts of which are given in Appendix II) the nominal rating as the mechanical output at the motor shaft which, on a one-hour's stand test at normal voltage with covers and cooling system arranged as in service, produces temperature rises not exceeding the limits specified in Appendix II (i.e. 100° C. or 120° C., based upon *resistance measurements*, or 75° C. or 95° C. by thermometer, for the windings, according to the class of insulation, *A* or *B*, respectively; 90° C. (thermometer) for the commutator). This test must be run on all new machines.

A commercial test on a traction motor will, therefore, include the following—

(1) A heat-run of one-hour's duration at the rated load.
(2) A speed test at full load, in each direction of rotation, to check the position of the brushes and to ascertain if the speed of the motor is within the permissible limits. (The speeds in each direction of rotation must be within $\pm$ 3 per cent of the rated speed.)
(3) A commutation test at 100 per cent overload.
(4) An insulation test, consisting of a brief application of high voltage.

With standard machines it is customary to test two similar machines together, operating one machine as a motor during the first half of the heat-run, and the other machine as a motor during the second half of the heat-run. The resistances of the armature and field windings of each machine are obtained at the start and finish of the run, in addition to the temperatures by thermometer.

The **special tests** under heading (*b*) include (*α*) an efficiency and speed test over the operating range of the motor, (*β*) a number of heat-runs at

various loads for the purpose of determining the thermal characteristics: (γ) a core-loss and saturation test.

Testing stands. Load tests are usually run on a testing stand, which is arranged to accommodate two similar motors. When tests with gearing are necessary the two machines are mounted on opposite sides of a horizontal shaft and are geared together through standard gearing. But for ordinary routine and efficiency tests the two machines are tested without gears, the armature shafts being arranged in line and coupled

FIG. 92.—Testing Stands for Traction Motors in Preston Works of English Electric Co.

together with a flexible coupling. Typical testing stands are shown in Fig. 92.

In cases where a single machine is to be tested the armature shaft is coupled to a brake, which should be either a Froude water-dynamometer or an electric regenerative dynamometer. The latter should be employed when the conditions are suitable, as the power generated in the dynamometer (less the losses in this machine) can be returned to the supply system, so that the net amount of power to be supplied for the test is only equal to the aggregate losses.

Fig. 93 shows a traction motor mounted on a test bed and coupled to an electric regenerative dynamometer in the traction research department of the English Electric Co. The dynamometer is a direct-current machine having its frame mounted on trunnion roller bearings and fitted with steel-yard arms for measuring the torque. Although the machine is capable of measuring torques up to 10,000 lb.-ft. it is very sensitive to

small variations of torque, and accuracies of the order of one-tenth of 1 per cent, at maximum torque, and one-quarter of 1 per cent at a torque of 2000 lb.-ft., are possible.

The dynamometer can also be employed for measuring the losses in the traction motor. For this purpose it is run as a motor, and the output (which is equal to the losses in the traction motor) is determined from measurements of the torque and speed.

Load tests on two similar machines. When two similar machines are to be tested, one is operated as a motor and is loaded by the other machine

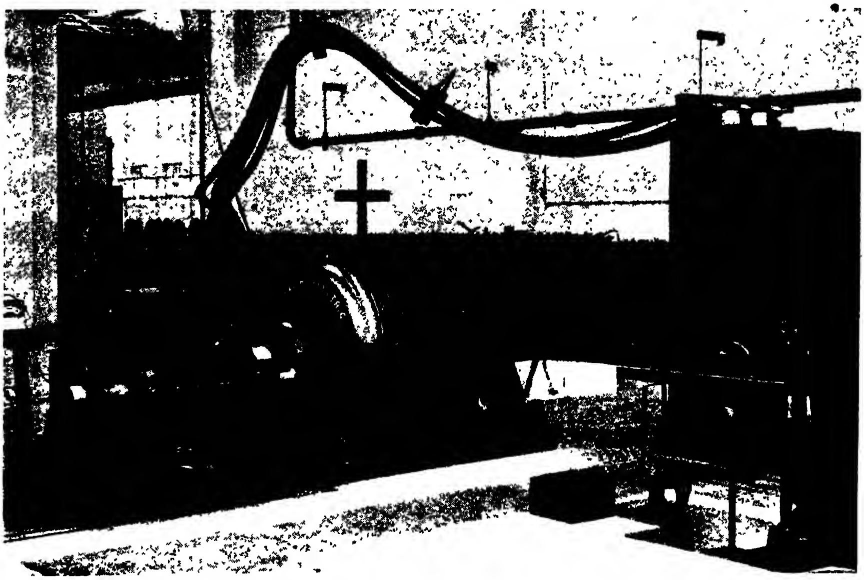


Fig. 93.—Electric Dynamometer in Traction Research Department of English Electric Co.

acting as a separately excited generator, the field winding being connected in series with the motor. The generator may be loaded either on rheostats or by feeding back into the supply. In the latter case a booster is required to make up the difference between the supply voltage and that of the generator armature, while in both cases a booster will usually be required to maintain a constant voltage at the terminals of the motor.

Elementary diagrams showing the connections of the machines and boosters for both methods of loading are given in Fig. 94. When the loading-back method is employed, the set must be started with the generator loaded on rheostats to prevent the machines reaching an excessive speed, the rheostat load being cut out as soon as the generator is paralleled with the supply. The load is then regulated by adjusting the field of the "load" booster, while normal voltage is maintained across the motor by regulating the field of the "line" booster.

A diagram of **connections of a switchboard** for carrying out these tests on a commercial scale is given in Fig. 95. With this switchboard it

is possible (1) to take load tests by either of the above methods ; (2) to operate either machine as motor in any desired direction of rotation ; (3) to lock the machines electrically against each other, so that the resistances of both machines may be determined without changing the main connections ; and (4) to provide for any of the special tests detailed below.

Thus, suppose No. 1 machine is to be tested as a motor by the loading-back method. Switch A is thrown up, switch B is thrown down, and

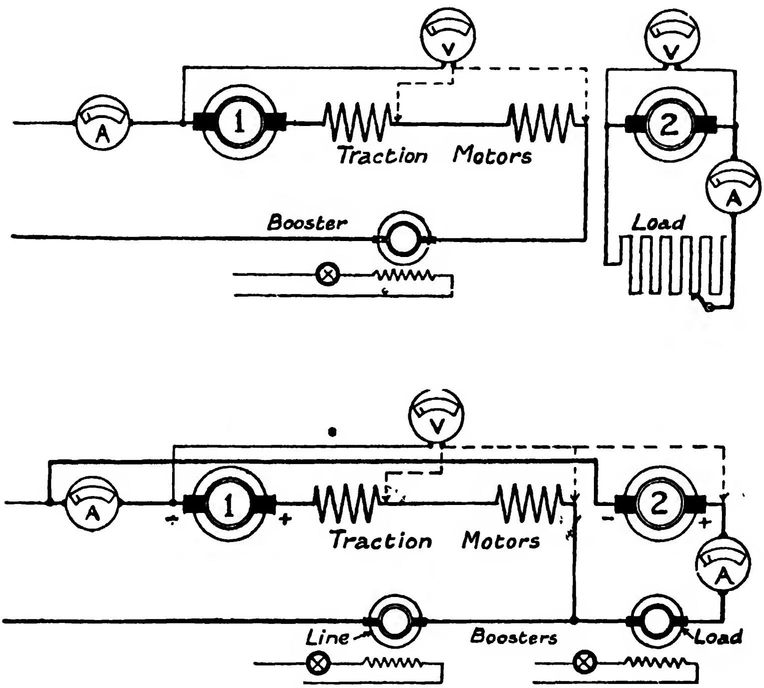


FIG. 94.—Connections for Load Tests on Traction Motors.

the reversing switch F is placed in the position for the desired direction of rotation. The set is started up on a rheostat load, and the voltage of the generator circuit adjusted (by means of the " load " booster) to equal the line voltage, when the paralleling switch E is closed and the rheostat load opened by switch H. The voltages across the paralleling switch are read on the voltmeter V by transferring the voltmeter plug to receptacles L, M. After the generator has been paralleled, the voltage across the motor is adjusted to the normal value by means of the " line " booster.

If the resistances of each machine are to be determined, switches A and B are kept in the above positions and switch E is closed, switches C, H being open, and the starting rheostat short-circuited. The armatures and fields of both machines are thereby connected in series with the " load " booster, which supplies the current for the tests. The torque of one machine is balanced against that of the other by throwing the

reversing switches in the proper positions, and under these conditions the machines will be locked against movement.

Efficiency tests. In running an efficiency test on the machines with the **generator loaded on rheostats** it is necessary to determine (*a*) the motor input, (*b*) the generator output, and (*c*) the loss in the generator field. The input and output currents are read on ammeters connected to

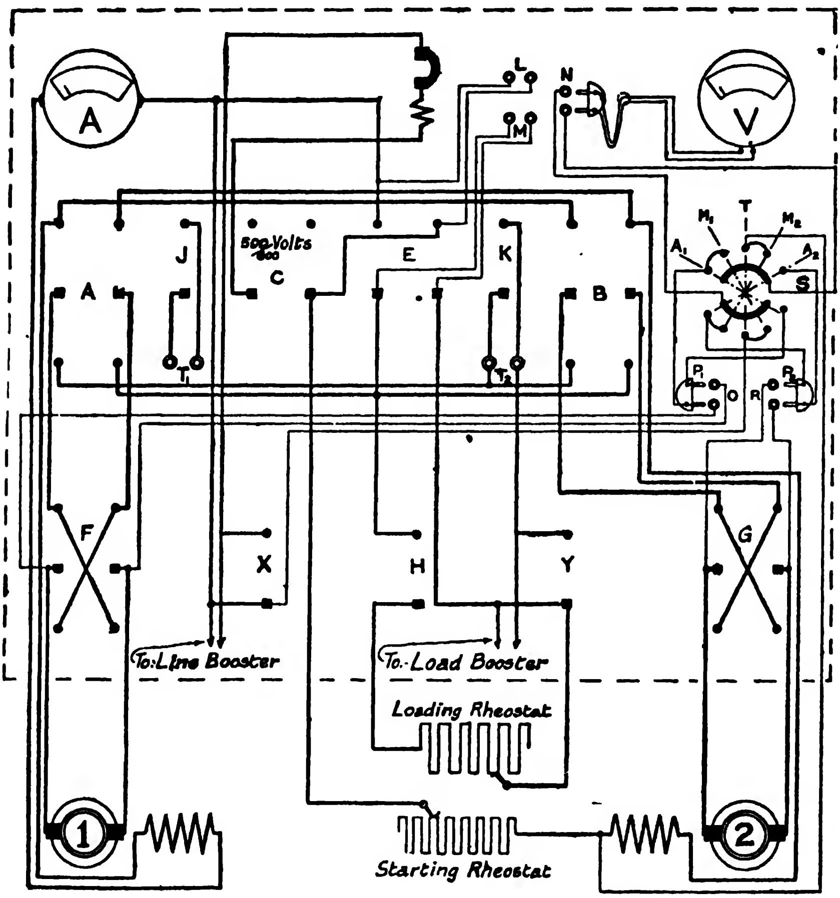


FIG. 95.—Connections of Switchboard for Testing Traction Motors.

the ammeter short-circuiting switches *J*, *K*, while the various voltages are read on the voltmeter *V*, by means of the multi-contact voltmeter switch *S*, the voltmeter plug being in receptacle *N*. To provide against the reversal of the voltmeter, when the direction of rotation is changed, the potential leads from the armatures are connected to the receptacles *O*, *R*, and connection to the voltmeter switch contacts is made by means of plugs P_1, P_2.

The **efficiency** of the machine operating as a motor is determined in the following manner—

Let V_1 = voltage across motor terminals,
V = voltage across motor and generator field (called the "total" voltage),
V_2 = voltage across generator armature,
I_1 = motor current in amperes (input),
I_2 = generator current in amperes (output).

Then the total losses are given by $VI_1 - V_2I_2$.

Now, since the generator field is connected in series with the motor and each machine is running at the same speed, the field I^2R, core, friction, and gear losses may be assumed as equal in each machine, while the armature I^2R losses are the only components of the total losses which

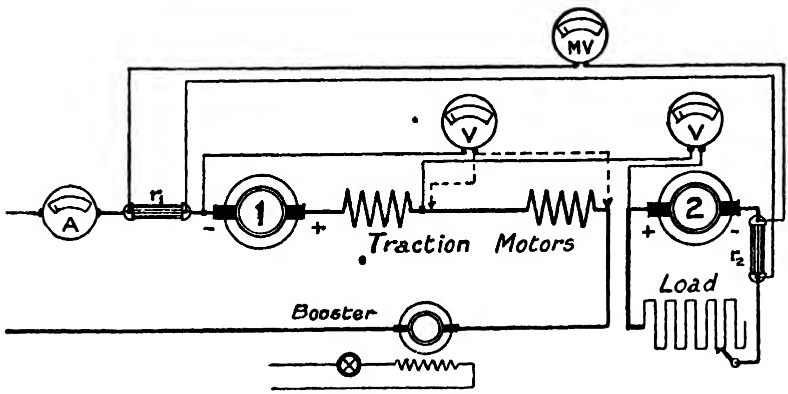


FIG. 96. -Connections for Efficiency Tests on Traction Motors.

differ in the two machines. If R_1, R_2 denote the resistances of the motor and generator armature respectively, the total loss in the motor is given by

$$\tfrac{1}{2}\{VI_1 - V_2I_2 - (I_1^2R_1 + I_2^2R_2)\} + I_1^2R_1,$$

and, since the motor output is V_1I_1, the efficiency is given by

$$\eta = [V_1I_1 - \tfrac{1}{2}\{VI_1 - V_2I_2 + (I_1^2R_1 - I_2^2R_2)\}]/V_1I_1$$

or $$\eta = 1 - (0{\cdot}5/V_1)\{(V + I_1R_1) - (I_2/I_1)(V_2 + I_2R_2)\} \quad . \quad (27)$$

a form which is convenient for calculation.

When a large number of results have to be worked up, the working is conveniently done in tabular form, as shown in the example in Table VII.

A greater degree of accuracy can be obtained by measuring directly the *differences* between the motor and generator currents and voltages, instead of determining each of these quantities separately. The connections are arranged as shown in Fig. 96*, r_1, r_2 being standard resistances,

* This method is due to Professor Ernest Wilson. See a paper read before Section G of the British Association, 1903. *Electrician*, vol. 51, p. 891.

or shunts, and MV a millivoltmeter, which is of such a range that a large deflection can be obtained for the maximum value of $(I_1 - I_2)$. If $(I_1 - I_2) = i$, and $(V_1 - V_2) = v$, then the efficiency is given by

$$\eta = 1 - \frac{0 \cdot 5}{V_1}\left[(V + I_1 R_1) - \frac{I_1 - i}{I_1}\{(V_1 - v) + R_2(I_1 - i)\}\right] \quad . \quad (27a)$$

TABLE VII

Method of Tabulation for Working out Efficiency Test

Rating of Motor, 28 h.p., 500 volts, 450 r.p.m. Tested with gears—gear-ratio 3·94 : 1.

Average Hot Resistances for Test—

Motor : Armature, 0·48 ohm ; brushes, 0·05 ohm ; field, 0·84 ohm ($\therefore R_1 = 0 \cdot 48 + 0 \cdot 05 = 0 \cdot 53$ ohm).

Generator : Armature, 0·465 ohm ; brushes, 0·05 ohm ; field, 0·84 ohm ($\therefore R_2 = 0 \cdot 465 + 0 \cdot 05 = 0 \cdot 51$ ohm).

Resistances at 75° C.—

Armature, 0·42 ohm ; field, 0·86 ohm ; brushes, 0·05 ohm. Total, 1·33 ohm.

Motor.				Generator.									
Volts V_1	Amperes I_1.	Speed.	Total Volts V.	Armature Volts V_2	Armature Amperes I_2	Field Amperes	$I_1 R_1$	$V + I_1 R_1$	$I_2 R_2$	$V_2 + I_2 R_2$	$\frac{I_2}{I_1}(V_2 + I_2 R_2)$	$V + I_1 R_1 - \frac{I_2}{I_1}(V_2 + I_2 R_2)$	$100 - 0 \cdot 1\{(V + I_1 R_1) - \frac{I_2}{I_1}(V_2 + I_2 R_2)\}$ = Per Cent. Efficiency
500	78	385	573	352	66	78	41·4	614·4	33·7	385·7	327	287	71·3
,,	70	405	567	369	59 5	70	37	604	30·3	399·3	340	264	73 6
,,	60	442	557	383	50·2	60	31·8	589	25 6	408 6	342	247	75·3
,,	50	482	542	408	39·8	50	26·5	568 5	20 3	428·3	341	227	77·3
,,	40	522	538	427	31·6	40	21·2	559	16 1	443	350	209	79·1
,,	30	600	528	443	22·3	30	15·9	544	11·3	454 3	338	206	79·4
,,	20	728	518	463	12 6	20	10·6	528	6 4	469 4	296	232	76·8
,,	12	1035	512	480	5 1	12	6·4	518	2 6	482·6	204	314	68·6

Calculation of characteristic curves from test results. In working out standard characteristic curves, such as those given in Figs. 26, 26A, the test readings are corrected for a copper temperature of 75° C., and for a gear and friction loss, at the rated load, equivalent to 5 per cent of the input (see Appendix II). Thus the actual gear loss, which would otherwise be a variable quantity in different machines of the same rating, is replaced by a definite quantity which is constant in machines of equal rating, and in this manner all characteristic curves are directly comparable.

When the loading-back method is employed the efficiency is best determined from direct measurements of the motor input and the total losses, rather than from the motor input and generator output, as the method is then equivalent to that (Fig. 96) in which the differences between the motor and generator currents and voltages are measured. The total losses are given by the sum of the input from the supply system and the outputs from the two boosters. Thus, employing the same

symbols as on p. 152, together with the additional symbols I and V_3 for the current input from the supply system and the voltage at the terminals of the "load" booster armature, respectively, we have

$$\text{Total losses} = VI_1 - V_2I_2 = VI_1 - (V - V_3)I_2$$
$$= V(I_1 - I_2) + V_3I_2 = VI + V_3I_2,$$

Hence the efficiency of the motor is given by

$$\eta = [V_1I_1 - \tfrac{1}{2}\{(VI + V_3I_2) - (I_1^2R_1 + I_2^2R_2)\} + I_1^2R_1]/V_1I_1$$
$$= 1 - 0{\cdot}5(VI + V_3I_2 + I_1^2R_1 - I_2^2R_2)/V_1I_1 \qquad (27b)$$

Therefore the readings to be taken when running an efficiency test by the loading-back method are: motor current and voltage, generator armature current, line or supply current, "total" voltage, "load" booster, armature voltage.

When it is desired to **separate the mechanical losses** (i.e. friction, windage, and gear loss, if any) from the electrical and magnetic losses (i.e. I^2R losses, "load" loss, and core loss) the set is run light—by supplying power to one machine at low voltage—and the input is measured over the range of speeds corresponding to the efficiency test. This input will then give the mechanical losses. The accuracy of the method, however, is not very high owing to the difficulty in obtaining steady readings of the input. A greater accuracy is possible by driving the set by a small motor and measuring the input to this machine, the procedure being somewhat similar to that employed for the core-loss test (p. 155), except that the fields of the traction motors are not excited.

The **speed is corrected** in the following manner—

Let R denote the resistance of the armature and field windings at a temperature of 75° C., R_1 the resistances during the test, n_1 the test speed, and n the corrected speed, both corresponding to a current I. If the terminal voltage during the test has been held at its normal value V_1, then

$$n_1/n = (V_1 - IR_1)/(V_1 - IR)$$

whence
$$n = n_1(V_1 - IR)/(V_1 - IR_1) \qquad (28)$$

If the speed n_1 has been determined at a voltage (V'_1) other than normal, then

$$n = n_1(V_1 - IR)/(V'_1 - IR_1).$$

The **speed curve** is usually plotted in miles per hour, corresponding to the diameter of wheel (D in.) and gear ratio (γ) to be used. Thus the speed, S (in ml.p.h.), corresponding to an armature speed n (r.p.m.), is

$$S = \frac{nD}{\gamma} \times \frac{60\pi}{12 \times 5280} = 0{\cdot}00297\,\frac{nD}{\gamma} \qquad (29)$$

The **torque curve** is obtained from the efficiency and speed curves. It is generally plotted in terms of the tractive-effort (expressed in lb.) at the driving wheels. Thus, for a current of I_1 and (normal) voltage V_1, the tractive-effort (F) in lb. is

$$F = \frac{V_1I_1\eta}{S} \times \frac{33000}{100 \times 746} \times \frac{60}{5280} = \frac{0{\cdot}005V_1I_1\eta}{S} \qquad (30)$$

η and S denoting the percentage efficiency and speed (ml.p.h.) respectively, which are obtained from the appropriate curves.

Core loss. The core loss (i.e. the iron loss in the armature core and the eddy-current losses (if any) in the armature conductors, armature flanges, etc.) may be determined by two methods, viz. (1) by driving the traction motor by a smaller shunt motor and measuring the input to the latter when the former is (*a*) unexcited, (*b*) excited with various field currents, the speed being held constant throughout; or (2) by running the traction motor light, with separately excited field, and measuring the input to the armature at various excitations, the speed for each excitation being obtained from the speed-curve of the motor. Although both of these methods are in use, method (1), notwithstanding its being a more lengthy process than method (2), is to be preferred when accurate results are required, since, by the proper choice of the driving motor, a

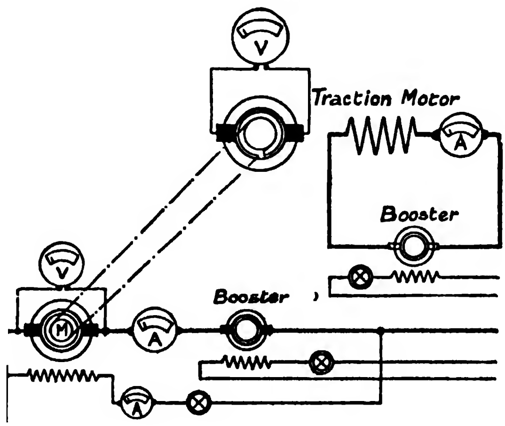


FIG. 97.—Connections for Core-loss Test on Direct-current Traction Motor.

large variation of the current input can be obtained between zero and maximum excitation on the traction motor.

When the core loss is derived by running the traction motor light, as in method (2), the variation in the current input is small, and, in consequence, the accuracy is not very great. This method, however, has the advantage of being performed quickly, and can be adopted when only a rough indication of the core loss is required.

Considering method (1) in detail, the procedure is practically the same as that adopted for a core-loss test on a direct-current generator or stationary motor. The armature shaft of the traction motor is belted to a small shunt motor of such a size that the maximum current input (corresponding to the maximum excitation on the traction motor) does not exceed 60 per cent of the full load current.* The field winding of this motor is separately excited, and the armature is run from a circuit of which the voltage is under control. The field winding of the traction

* Generally, the rating of the driving motor should be about 10 to 15 per cent of that of the machine under test. To obtain good results the following conditions should be fulfilled—

(1) Maximum current input to driving motor should not exceed 60 per cent of the full load current; (2) input current when driving the machine under test unexcited should not exceed 20 to 25 per cent of the full load current.

motor is separately excited from a low voltage supply. Instruments are connected in the armature and field circuits of both machines, as indicated in Fig. 97. A series of readings are taken at various exciting currents on the traction motor (from zero to the maximum), the field current of the driving motor being maintained at a constant value, and the speed being held constant throughout by adjusting the voltage supplied to the armature. Under these conditions the core loss for a given exciting current is given by the increase in the input to the driving motor (corrected for I^2R loss) between zero excitation and the given value. A typical set of readings and the values of the core loss deduced therefrom are given in Table VIII. Similar sets of observations will be required at other speeds in order to obtain the "characteristic core-loss curve" (which shows the "no-load" core loss at any exciting current when the motor is supplied at constant voltage).

The results of the separate core-loss tests are plotted with exciting current as abscissae, and the speed-curve of the motor is plotted on the same sheet, as shown in Fig. 98. The **characteristic core-loss curve** is obtained as follows: The currents corresponding to the speeds of the individual core-loss tests are determined from the speed curve and are projected on to the appropriate core-loss curve. In this manner a single point is obtained on each core-loss curve, and the curve through these points is the characteristic core-loss curve.

If speed curves corresponding to voltages other than normal are also plotted, the characteristic core-loss curves for these voltages can readily be obtained.

TABLE VIII

TYPICAL SET OF READINGS FOR CORE-LOSS TEST

Resistance of Armature Circuit of Driving Motor = 1·12 ohms.

Machine under Test.			Driving Motor.			Input to Driving Motor (Watts).	I^2R Loss in Armature Circuit of Driving Motor (Watts).	Input less I^2R Loss (Watts).	Core Loss (Watts).
Speed.	Field Amperes.	Armature Volts.	Armature Volts.	Armature Amperes.	Field Amperes.				
400	0	..	188	3·02	0·6	568	11	557	..
,,	20	367	192	5·03	,,	966	28	938	381
,,	25	401	192·5	5·67	,,	1092	36	1056	499
,,	30	423	193	6·3	,,	1216	44	1172	615
,,	35	443	194·5	6·82	,,	1327	52	1275	718
,,	40	463	195·5	7·47	,,	1460	63	1397	840
,,	45	475	196·2	7·9	,,	1550	70	1480	923

The saturation curve of the motor is obtained at the same time as the core-loss test by observing the armature voltage at each value of the exciting current. The flux is then calculated and plotted against the exciting current, or the ampere-turns per spool.

In the second method, the field of the traction motor is separately excited and the armature is run light from a variable voltage supply. Readings are taken of the input to the armature at various values of

the exciting current and speed (the speed for a given excitation being adjusted to that corresponding to this current on the speed-curve). The input so obtained is equal to the core, friction, and windage losses.

To separate the core loss from the friction and windage loss the machine is run light—as a series motor—on a low voltage circuit, and the input to the armature is observed for speeds corresponding to those in the previous test. Since the excitation will be very low, the input to the armature may be taken as equivalent to the friction loss. Provided that the speeds have been correctly adjusted, the difference between the

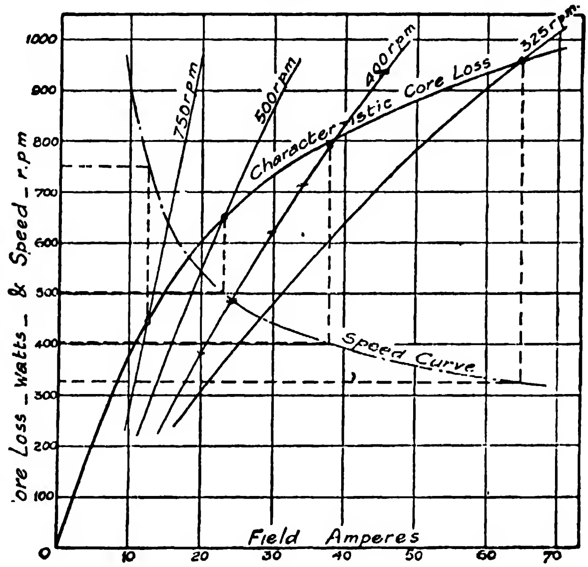


FIG. 98.—Results of Core-loss Test on Traction Motor.

two tests will give the characteristic core-loss curve without further calculations.

A modification of the above method which is sometimes adopted is shown in Fig. 99. In this case the armature is connected in series with the field winding, but is shunted with a variable resistance R, and the machine is run light from a 500 volt circuit. The field current is adjusted by varying the shunt resistance R, and the speed is adjusted to the precise value by the rheostat r It will be realized that this method is extremely wasteful, and its use should be restricted to the smaller traction motors when no low-voltage supply is available.

A condition essential to all core-loss tests is that readings must only be taken after the speed has become steady. When method (1) is adopted, it is necessary to take precautions against an alteration of the friction during the individual tests.

Core-loss tests, such as carried out by any of the methods outlined above, give the core loss corresponding to " no-load " conditions (i.e. with undistorted main flux). When the motor is loaded the effects of armature reaction cause distortion of the main flux and result in higher core losses

in the armature teeth, together with higher eddy-current losses in the armature conductors. These additional losses are called "load" losses, and are of considerable importance in machines working with tapped fields in consequence of the field distortion being greater in these machines than in machines working with full field. This matter has been investigated by Dr. F. W. Carter and is discussed at length in a paper on "Rating and Service Capacity of Traction Motors" (*Journ. I.E.E.*, vol. 65, p. 994).

Thermal characteristic. The thermal characteristic of a traction motor is a curve showing the time that the motor will carry various loads, at normal voltage, for a temperature rise of 75° C., the machine being at atmospheric temperature at the start. The characteristic is determined by carrying out heat runs at different loads and normal voltage. In each run the temperatures of those field coils which are accessible are

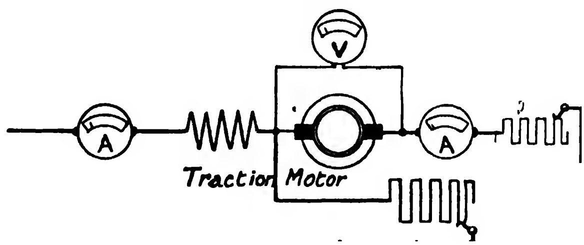


FIG. 99.—Connections for Core-loss Test by Running-light Method.

recorded every 15 minutes. The machine is shut down when the temperature reaches 75° C., and the temperatures of all parts are obtained. In many cases, however, the thermal characteristic of the armature is not identical with that of the field, and in some cases the armature heating is the limiting feature at all loads. Under the latter conditions the runs will have to be stopped before the field winding has attained the standard temperature rise (75° C.), and, if the temperature rise of the armature differs appreciably from this value, the length of the run to give the standard temperature rise will have to be obtained either by extra-polation or from another heat-run at the same load.

In large motors the armature heating is generally limiting for all loads, but in small motors the field heating may be limiting at heavy loads, and the armature heating limiting at light loads. The thermal characteristic in this case will not be a smooth curve, but will consist of portions of the thermal characteristics of the armature and field.

The thermal characteristic is useful in showing how the temperature of a motor is affected by steady loads of definite duration. But the continuous rating of the motor obtained from this characteristic will differ from the continuous rating of the machine when operating under service conditions, on account of the distribution of losses not being the same in each case.

When the service on which a given motor has to operate is known, the approximate temperature rise of the machine can be obtained from a heat-run, on the testing stand, in which the losses in the motor are

equivalent to, and distributed in the same ratio as the average losses in service, the ventilation being, as far as practicable, the same as in service. The heat-run is continued until a constant temperature is reached. The temperature rise obtained by this method, however, is usually slightly higher than that obtained in service, on account of the better ventilation in the latter case.

The method of obtaining the voltage and current at which this test must be conducted is as follows. From the service speed-time curves the corresponding curves of the voltage and current for each motor are obtained. The mean voltage and r.m.s. current are then calculated over the whole period in which the motor is in service, and these values adopted for the heat-run. It is apparent that the losses in the motor during this test will have the same value as the average losses in service, and, moreover, the ratio of the distribution will be the same in each case.

When this test is run on a self-ventilated machine, the speed of the armature during the test must be equal to that corresponding to the average speed in service. The voltage corresponding to this speed may differ from the mean voltage in service, and in this case the test must be run with the total armature loss and the field loss equivalent to the average values obtained above, although the ratio of the armature I^2R loss to the core loss may not be the same in the two cases.

PART II

Factory Tests on Single-phase Traction Motors

The **commercial test** applied to a single-phase motor is similar to that applied to a direct-current motor. The motor is run for one hour at its rated load with normal voltage and frequency, the resistances and temperatures being obtained in the usual manner. This test is followed by a speed test in each direction of rotation, a commutation test at various loads, including starting, and an insulation test. In addition, the impedance of the motor is measured at normal frequency with the armature stationary.

The loading-back method cannot be applied conveniently to single-phase motors, and in consequence the load must take the form either of a direct-current generator or a mechanical brake (e.g. the Froude water dynamometer). With series motors, two machines may be coupled together (or mounted on a test stand in a similar manner to direct-current motors) and one machine operated as a separately-excited direct-current generator. This arrangement is convenient for heat runs and load tests, but for efficiency tests the losses in the generator must be known. Alternatively, the motor may be loaded on a brake and the output determined mechanically.

In **efficiency tests** readings are obtained of the input (by wattmeter and ammeter), torque and speed over a range of loads at constant voltage and frequency. The readings are then corrected to a definite copper temperature and gear loss (if any) in a manner similar to that adopted for direct-current motors, and the efficiency and power-factor calculated, while the torque and armature speed are converted into tractive-effort

and train speed, to correspond to the operating conditions. The results are then plotted against input amperes (as abscissae), thus giving the characteristic curves of the motor.

For the calculation of speed-time curves, the characteristic curves must be supplemented by others, showing the performance of the motor when operating at the voltages corresponding to the various tappings on the main transformer; while, for the calculation of energy consumption and the load on the distributing system, the input to the primary of the main transformer will be required. In cases where each motor is fed from a separate transformer—as in some locomotives—the characteristic curves of the transformer are combined with those of the motor. When two or more motors are supplied from one transformer, the correct

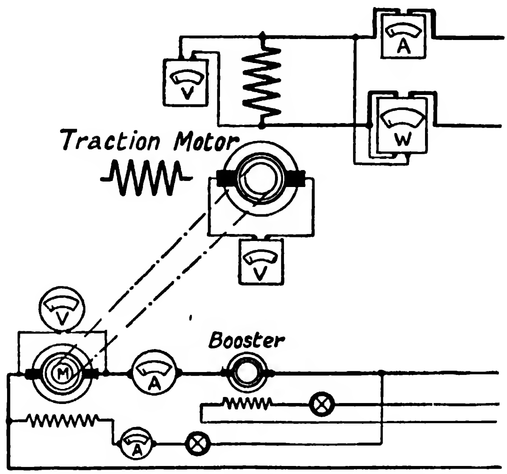


FIG. 100.—Connections for Core-loss Test on Compensated-series Motor.

proportion of the transformer losses must be allocated to each motor in determining the combined efficiency curve.

Core loss. In single-phase motors core losses occur in the field structure (or stator core) as well as in the armature core. The loss in the latter consists of two components, one due to the alternating flux and the other due to the rotation of the armature. The core loss in the stator (and the component of the armature core loss which is due to the alternating flux) is supplied by the exciting current, and can therefore be measured by a wattmeter in this circuit. The other component of the armature core loss (which is due to the rotation of the armature) is determined by measuring the power required to drive the armature. In these tests the brushes must be raised from the commutator, as otherwise the copper losses in the field and armature windings (resulting from the circulating currents in the coils short-circuited by the brushes) will be included with the core losses.

To determine the magnitude of the losses due to the circulating currents, it is the practice, in core-loss tests, to take two tests, one with

all brushes on the commutator and the other with all brushes raised from the commutator.

The **method of procedure** is as follows. The exciting winding is separately excited from a variable voltage supply of the correct frequency, and a wattmeter, an ammeter, and a voltmeter are connected in the circuit. (Fig. 100.)

The armature is driven at various speeds from a small shunt motor, the armature of which is connected to a variable voltage supply, while the field is separately excited at a constant current. An ammeter and a voltmeter are connected in the armature circuit of the driving motor.*

The brushes of the motor under test are removed, and a series of readings are then taken over a range of exciting currents (from zero to

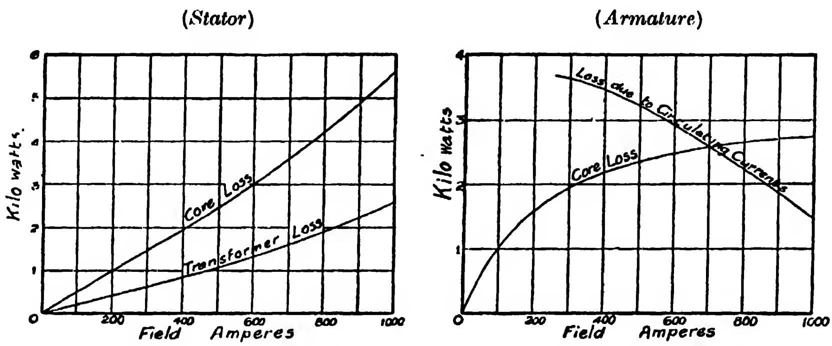


FIG. 101.—Results of Core-loss Tests on Compensated-series Motor.

about 50 per cent overload) at four or five different speeds,† the speed being maintained constant for each set of readings. In this manner both components of the rotor core loss, together with the stator core loss, are determined at the same time. Provided that there are no circulating currents in the armature due to transformer action,‡ the wattmeter in the field circuit will measure the core loss in the stator and armature (due to the alternating flux) + the I^2R loss in the field winding. Similarly, the input to the driving motor, when corrected for the I^2R loss in its armature, will, in the absence of circulating currents, represent the core loss (due to the rotation of the armature) + the friction and constant losses in the set. The latter are, of course, given by the corrected readings corresponding to zero excitation on the machine under test.

The corrected readings are plotted with exciting current as abscissae. One curve is obtained for the component of the core loss which is due to

* For the relation between the sizes of this motor and the machine under test, see footnote on p. 155.

† Or for each value of the exciting current the corresponding speed is obtained from the speed-curve and readings taken at this speed with and without excitation. In this manner the points on the characteristic core-loss curve are determined directly, but the results will be affected to a much greater extent by inaccuracies in individual readings than when the test is conducted in the manner detailed above. Moreover, the results only give the characteristic core-loss curve for one operating voltage.

‡ Circulating currents may be produced in multiple-circuit armature windings if they are unbalanced magnetically or electrically.

the alternating flux, and a set of curves—similar to those in Fig. 98—is obtained for the component of the core loss which is due to the rotation of the armature. The characteristic core-loss curve is derived from these curves in the manner already shown.

Fig. 101 represents the results of a core-loss test.

In order to determine the **losses** (due to circulating currents) **in the armature coils** which are short-circuited by the brushes, the above tests are repeated with all the brushes in position. The wattmeter reading in this case includes the losses (due to transformer action) in these coils, and also any additional iron losses due to the reaction of the circulating currents. Similarly, any losses in the armature due to the coils cutting leakage fluxes in the neutral zone, or by magnetic or electric dissymmetry, are included in the input to the driving motor.

PART III

SERVICE TESTS

Service tests can be grouped into two classes, viz. (1) those which are conducted under *actual* service conditions, involving runs of various lengths (corresponding to the distances between the stations) at a given mean schedule speed ; and (2) those which are conducted under *equivalent*, or average, service conditions, on level track, for the purpose of obtaining data of the motors.

The tests in class (1) are of the order of "official" tests, and are usually run to ascertain if a given equipment fulfils the manufacturers' guarantees ; while those in class (2) are of the nature of experimental tests, the object of which is the determination of data from which the "service-capacity" curves of the motors can be obtained. These curves show the mean schedule speeds at which a motor is capable of operating various services with a given temperature rise ; the nature of the service being expressed by (*a*) the number of stops per mile, (*b*) the train weight per motor. A typical set of curves for a particular motor is given in Fig. 102.

Now the heating due to the I^2R and core losses depends upon the magnitude and distribution of these losses, and will vary with the class of the service. Thus, in suburban service, the greater portion of the I^2R losses occurs during acceleration and speed-curve running ; while the core loss has its greatest value at the end of the accelerating period, and will probably exceed the armature I^2R loss during the free-running period. On account of the large thermal capacity of the motor, the temperature of the various parts will not follow appreciably the fluctuations in the losses, and a steady temperature will be attained when the average rate of generation of heat is balanced by the rate at which the heat can be dissipated in radiation, convection, etc.

To determine the service capacity curves of a motor it must be operated under uniform service conditions (corresponding to a particular service) until the temperature has attained a constant value. Having decided the class of service (i.e. the schedule speed, stops per mile, and train weight per motor) an appropriate speed-time curve is drawn, from which, in combination with the characteristic curves of the motor, the

accelerating current, the time during which power is "on," the coasting time, braking time, and duration of stop are obtained.

A car equipped with motors and loaded to the required weight per motor is then operated on level track to this speed-time curve, the runs being continued until the temperature of the motors becomes steady. Additional tests are made for other service conditions, the motors being at the atmospheric temperature at the start of each test. The line

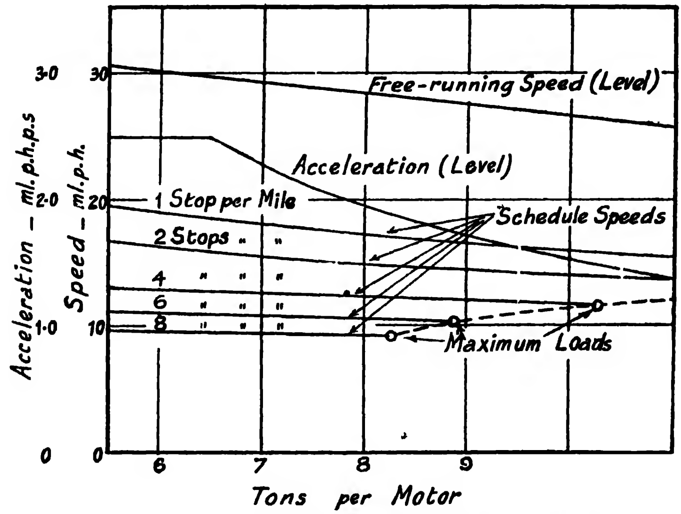


FIG. 102.—Service-capacity Curves for Tramway Motor. (B.T.-H. Co.)

voltage in all tests is maintained, as far as practicable, at the normal value. Provided that the service conditions under which the tests are run have been selected to give the same limiting temperature rise in each case, the service capacity can be obtained directly from the tests.

The determination of a number of service-capacity curves in this manner would consume too much time, as each test requires about 10 to 12 hours or more. Moreover, since any number of service-capacity curves can be calculated from the service thermal characteristic of the motor, it is necessary to perform only sufficient tests to determine the latter.

The method by which the **service thermal characteristic** of the motors is determined is as follows. Records are obtained of the current and voltage by means of suitable graphic-recording instruments, while the temperatures of the field and frame are observed at frequent intervals, and the final temperatures of all parts are ascertained at the completion of each test.

The resistances of the field and armature windings are taken, if possible, during the lay-over periods.

The I^2R losses in the armature, brush contacts, and field windings are calculated.* The core loss corresponding to the various excitations

* In some cases the I^2R loss in the field coils has been determined directly, by means of an integrating wattmeter connected in the field circuit. The average loss

and speeds is obtained from the core-loss curves, and the "load" loss and other indeterminate losses causing heating are obtained from the segregated losses deduced from the stand efficiency test. In this manner the total losses in the motor are determined for a series of runs. From the average losses and the highest observable temperature rise the watts dissipated per degree rise of temperature is computed for each run and is plotted against the mean running speed. Hence from this curve (which usually approximates very closely to a straight line) the temperature rise

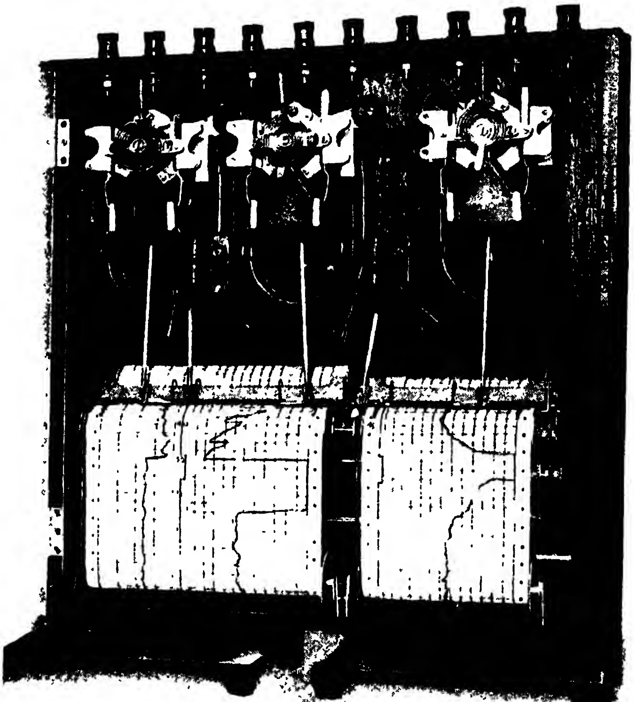


FIG. 103.—Evershed and Vignoles Traction Recorder.

[The records shown on the charts, reading from left to right are: line volts; duration of stop; current; duration of brake application; speed.]

for any service can be predetermined when the corresponding average losses and the mean running speed are known.

On "**official**" **service tests** the energy consumption, temperature rise of the motors, and schedule speed have to be determined. With direct-current equipments it is the practice to record the line voltage and the current input to one motor. With alternating-current equipments,

is then obtained by dividing the watt-hours registered during the test by the duration of the test (in hours). If the average resistance of the field coils is also determined, the square of the average current during the test can be readily obtained, which, when multiplied by the average armature resistance, will give the average armature I^2R loss.

however, the current and power input, together with the line voltage, must be determined on the high-tension side of the main transformer.

Graphic recording instruments for train testing must be designed to withstand the large amount of vibration incidental to train operation, and are usually distinguished from the commercial forms of recording instruments by the high torque and large damping of the moving element.

A typical instrument is illustrated in Fig. 103. This instrument gives records of five different quantities—viz. current, voltage, speed, duration of brake applications, duration of stops—on two charts, which are driven by clockwork from a common spindle. The speed record is obtained by recording the voltage of a magneto-generator coupled to one of the

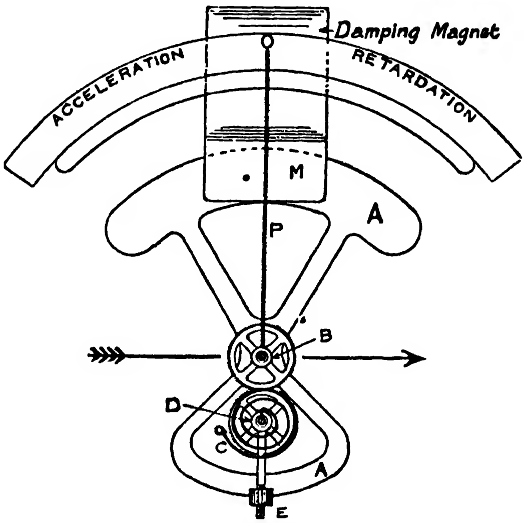


FIG 104.—Diagram illustrating principle of Wimperis Accelerometer.

wheels, an adjustable resistance in the circuit providing the means whereby the chart record is given directly in miles per hour. The duration of the brake applications is recorded by a pen operated by an electromagnet, which is controlled by contacts on the brake cylinder. The duration of the stops is recorded by a second electromagnetic pen controlled by a push button operated by an observer.

The records are obtained in rectangular co-ordinates, and the effects of vibration are neutralized by arranging the pens to move on a horizontal surface and by heavily damping, by oil dashpots, the moving systems of the ammeter, voltmeter, and speed recorder.

With the introduction of a reliable instrument for the **direct measurement of acceleration and retardation,** it is now the practice to determine these quantities directly, instead of relying on the speed record. The instrument used for this purpose is usually the **Wimperis accelerometer,** which is made in both the indicating and recording types.

In each type of instrument the moving element consists of an aluminium sector A (Fig. 104) fixed to a spindle B, which is mounted

vertically in jewelled bearings. Since the centre of gravity of the sector is not coincident with the axis of rotation, any force resulting from acceleration will cause a rotation of the spindle and a deflection of the pointer P, provided that the direction of the force is not in the plane containing the centre of gravity and the axis. The rotation of the spindle B is restrained by a hair-spring C, fixed to another spindle D, which is geared to the former spindle by 1 : 1 gearing. The spindle D

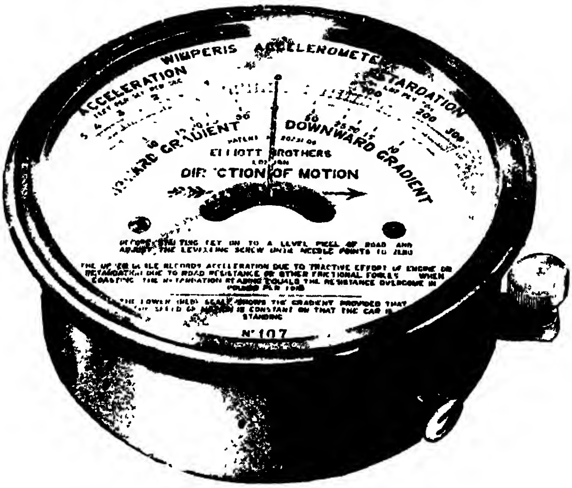


FIG. 105.—Wimperis Indicating Accelerometer (Elliott Bros.).

also carries a compensating balance-weight E, which is adjusted to have a moment of inertia equal to that of the sector and pointer, the centre of gravity of the sector and compensating balance-weight being contained in a plane passing through D and B. In this manner the sector and compensating balance-weight will have equal and opposite moments about the spindle B in a direction at right angles to the motion. The instrument is therefore only affected by accelerating forces which have a component along the direction of motion, and it is eminently suited for train testing.

A view of the indicating type of instrument is given in Fig. 105.

CHAPTER VIII

THE CONTROL OF DIRECT-CURRENT TRACTION MOTORS

PART I

General Principles

Duty-cycle. In selecting a suitable method of control for an electric motor, or a group of motors, a knowledge of the duty-cycle is necessary. With tramway and suburban railway services the duty-cycle consists of (1) a starting period at high current input—of from 10 to 20 seconds' duration—(2) a speed-curve-running period during which the acceleration and the current input diminish gradually, (3) a coasting period, (4) a braking period, (5) a brief period (from 10 to 20 seconds) of rest. A typical duty-cycle corresponding to suburban service is shown in Fig. 25 (p. 64).

The frequency varies from 15 to 20 duty-cycles per hour for suburban service up to about 60 duty-cycles per hour for tramway service.

As the average current input to each motor during the starting period is usually of the order of the rated current, a considerable loss of energy would occur if the motors were started with a series rheostat. But, since the operating conditions on tramways and suburban railways necessitate the use of multi-motor equipments—tramcars being equipped with two, and in certain cases four, similar motors, and motor-coach suburban trains being equipped with four or more similar motors—alternative methods of control are available by grouping the motors in series and parallel. These combinations may be utilized during starting because the torque of a series motor depends only upon the current input to the motor, and therefore with a multi-motor equipment two or more similar motors, when *connected in series*, will produce the same total torque as when they are connected in parallel, provided that the current per motor is the same in both cases.

The series combination of a multi-motor equipment, however, can only be employed during the initial portion of the starting period, as the parallel combination is necessary to obtain full speed.

Therefore, with a two-motor equipment, the motors may be connected in series during the first portion of the starting period and in parallel for the remainder of the period. With a four-motor equipment three combinations of the motors are possible, viz. (1) series, (2) series-parallel, (3) parallel. These methods of starting are called "series-parallel" and "double-series-parallel" control, respectively. They not only result in considerable saving in energy compared with the rheostatic method of starting, but also provide two and three efficient running speeds.

Energy loss at starting. First consider two similar motors to be started by the series-parallel method. Let the line voltage be constant and the motor current be maintained at a constant value, I, throughout the starting period.

The current-time and voltage-time diagram for the starting period is shown in Fig. 106, in which the motor current is represented by the

horizontal line ABC drawn at ordinate I, the line current by the stepped line $ABDE$, and the line voltage by the horizontal line XYZ drawn at ordinate V. The voltage drop in one motor, due to the current I, is represented by OF, and the voltage drop in the two motors when connected in series by OG ($= 2OF$). The starting period is represented by OM, of which the portions ON, NM correspond to the series and parallel connections respectively of the motors. The point N is determined by the condition that the connections must be changed from series to parallel when the voltage per motor is equal to one-half of the line voltage. Hence, if a horizontal line be drawn through the ordinate corresponding to half

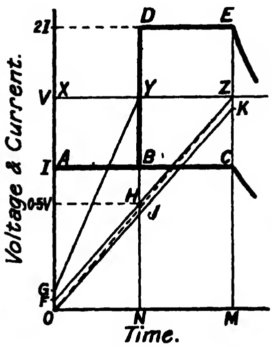


FIG. 106

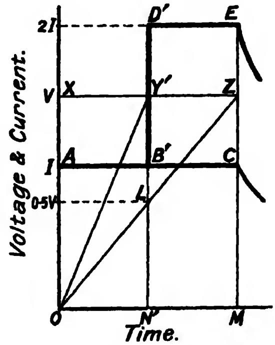


FIG. 107.

Starting Conditions for Series-parallel Control.

line voltage, the point of intersection, H, with the line ZF gives the abscissa required.

The point, N, and the **durations of the series and parallel portions of the starting period,** are easily determined analytically. Thus, if T denotes the duration of the starting period, t_s, t_p the durations of the series and parallel portions respectively, V the line voltage, and v the voltage drop in each motor corresponding to the current I, then, from the similar triangles OJN, OKM, we have

$$\frac{t_s}{T} = \frac{JN}{KM} = \frac{\frac{1}{2}V - v}{V - v}$$

whence $$t_s = \tfrac{1}{2}T(V - 2v)/(V - v)$$

and $$t_p = T[1 - \tfrac{1}{2}(V - 2v)/(V - v)]$$

The variation of voltage at the terminals of the two motors during the series portion of the starting period is represented by GY, and the variation of voltage at the terminals of *each* motor throughout the whole starting period is represented by FZ. Hence the variation of the counter-E.M.F. of each motor throughout the starting period is represented by OK; ZK being equal to OF (which represents the voltage drop in one motor due to the current I).

Hence ordinates between XY and GY represent the voltage drop in the starting rheostat when the motors are connected in series. Similarly ordinates between YZ and HZ represent voltage drop in the starting rheostat when the motors are connected in parallel and the line current is $2I$.

Therefore the energy loss in the starting rheostats during series

running is represented by the product of the *motor* current and the triangular area XGY. Similarly the energy loss in the rheostats during parallel running is represented by the product of the *line* current and the triangular area YHZ.

For the **ideal case,** when the voltage drop in the motors is negligible, the current-time and voltage-time diagram takes the form of Fig. 107, in which the counter-E.M.F. and terminal voltage per motor are both represented by the line OZ. The duration of the series portion (ON') of the starting period is now equal to that of the parallel portion ($N'M$). The energy loss in the starting rheostats during series running is proportional to the triangular area XOY', and that during parallel running is proportional to twice the area $Y'LZ$, i.e. to the area XOY' (since $Y'Z = XY'$, and $Y'L = \frac{1}{2}OX$). Thus the energy loss during starting is divided equally between the series and parallel periods. The total energy loss during starting is proportional to the area of the rectangle $OXY'N'$.

Now the energy output from one motor during the whole starting period is represented by the product of the motor current and the triangular area OZM : it is, therefore, proportional to the area OZM. Hence the output from the two motors during the starting period is proportional to the area of the rectangle $OXZM$. Therefore *the total loss of energy in the starting rheostats is equal to one-half of the energy output from the motors during the starting period.*

Energy saving due to series-parallel control. Since the energy taken from the supply system = energy output from motors + losses in rheostats, therefore, with series-parallel control, the energy taken from supply system = 1·5 × energy output from motors, and the overall efficiency during starting = 1/1·5 = 2/3, or $66\frac{2}{3}$ per cent.

With rheostatic control throughout the whole of the starting period (i.e. with the motors connected permanently in parallel) the energy loss in the rheostats is proportional to twice the area OXZ, i.e. to the area of the rectangle $OXZM$, Fig. 107. Thus in this case the energy loss in the rheostats is equal to the energy output from the motors, and the overall efficiency is 50 per cent.

Series-parallel control, therefore, results in a saving of energy equal (*in the ideal case*) *to one half of the energy output of the* (*two*) *motors during the starting period.*

Other important advantages of series-parallel control are two speeds are available in the ratio of 1 : 2, approximately ; the starting rheostats are smaller, lighter, and cheaper than those necessary for ordinary rheostatic control under similar conditions.

Energy saving due to double series-parallel control. When four similar motors are available, three combinations of the motors are possible, viz. series, series-parallel, and parallel. Hence with ideal starting conditions, i.e. negligible voltage drop in the motors, constant current per motor, and constant line voltage—the durations of the series and series-parallel portions of the starting period are each equal to one-fourth of the whole starting period. It is easy to show that under these circumstances the energy loss in the starting rheostats for the series and series-parallel periods is equal to one-half of that for the parallel period, and that the energy loss during the parallel period is equal to one-fourth of

the energy output from the motors during the whole starting period. Thus the overall efficiency $= 1/(1 + \frac{1}{4} + \frac{1}{8}) = \frac{8}{11}$, or 72·73 per cent.

When six similar motors are available and each motor is wound for one-half of the line voltage—as is the practice with 3000-volt equipments—the three motor combinations are: (1) series, (2) first series-parallel with two groups each consisting of three motors connected in series, (3) second series-parallel with three groups each consisting of two motors connected in series. In this case, with ideal starting conditions, the durations of the three portions of the starting period are all equal, and the energy loss in the starting rheostats is equal to one-third of the energy output during the whole of the starting period. Therefore the overall efficiency in this case is $1/(1 + \frac{1}{3}) = \frac{3}{4}$, or 75 per cent.

Comparison of rheostatic, series-parallel, and double series-parallel control. The comparison for ideal starting conditions is shown in the accompanying table, in which is also given the approximate ratio of speeds for the various combinations of the motors when the rheostats are cut out and the motor current has a given value.

System of Control.	No. of Speeds Available.	Approx. ratio of speeds.	Rheostatic Losses as Percentage of Energy Output. (Ideal Conditions.)	Overall Efficiency during Starting. (Ideal Conditions.) Per cent.
Rheostatic Parallel		- -	100	50
Series-Parallel		1 : 2	50	66·6
Double series-parallel (4 motors)		1 : 2 : 4	37·5	72·7
Double series-parallel (6 motors)		1 : 2 : 3	33·3	75

Applications of double series-parallel control. The principal applications of double series-parallel control are to be found in freight locomotives in which a large number of control notches and slow-running speeds are essential. With suburban trains a slow-running speed is unnecessary, and the slight saving in energy of double series-parallel control compared with series-parallel control would be entirely offset by the additional cost, weight, and maintenance of the double series-parallel equipment.

Practical requirements. In the practical application of series-parallel and double series-parallel control the starting must be effected with a limited number of steps in the starting rheostat, in order to avoid excessive cost, and complication of the controller. Therefore the motor current during starting cannot be maintained at an absolutely constant value, as hitherto assumed, but varies between definite limits as the sections of the rheostat are cut out. By suitable design of the rheostats and correct manipulation of the controller a given average value of the motor current can be maintained throughout the starting period, as indicated in Fig. 108. To obtain this result with series-parallel control, it is necessary that the change of motor combinations from series to parallel be made when all the rheostat has been cut out and the motor current has decreased to its lower limit—i.e. at point A, Fig. 108.

The change of motor combinations from series to parallel necessitates the re-insertion of a portion of the starting rheostat in order to limit the motor current to the prescribed value. The rheostats may be re-inserted according to either of the alternative methods shown in Fig. 109, both of which are extensively employed in practice. If the (motor) current limits during parallel running are to be the same as those during series running the value of resistance cut into the motor circuit when the motors are first connected in parallel must be such that the upper limit

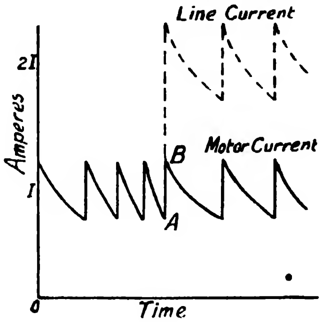


FIG. 108.—Variation of Current during Starting.

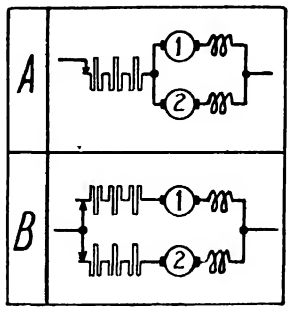


FIG. 109.—Alternative Methods of Connecting Motors and Rheostats.

of current (i.e. point B, Fig. 108) is obtained. The methods of calculating the requisite values of resistance to satisfy these conditions are discussed later.

The starting conditions represented in Fig. 108, in which uniform variation of motor current occurs during the whole of the starting period, may be considered as ideal for the limited number of steps which can be

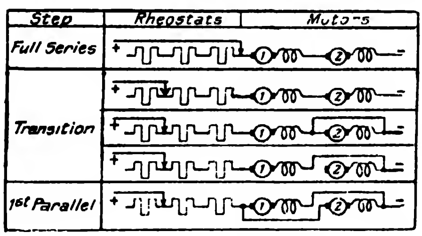


FIG. 110.—Shunt Transition.

employed in practice. These ideal conditions necessitate that the transition be effected without interrupting the current in either motor—a result which may be accomplished by the "bridge" method. In many cases, however, the complication entailed in the controller with this method of transition is not warranted, and a simpler method, called "shunt" transition—in which one motor only is supplied with current during transition—is employed. These methods will now be discussed in detail.

Shunt transition. Three transition steps are necessary, the connections being shown in Fig. 110. At the first step a portion of the starting rheostat is re-inserted, the motors being still connected in series. The

value of this resistance should be such that the current input on the second transition step (when one of the motors is short-circuited) is approximately equal to the upper limit of current during the starting period (i.e. point *B*, Fig. 108). At the second step one motor (No. 2) is short-circuited by connecting the negative terminal of motor No. 1 directly to the negative supply main. At the succeeding step the series connection between the motors is opened, so that motor No. 2 is now ready to be connected in parallel with motor No. 1, thus completing the transition.

Bridge transition. This is effected in a single step without opening either of the motor circuits. The starting rheostats, however, must be divided into two separate portions, so that when the motors are operating

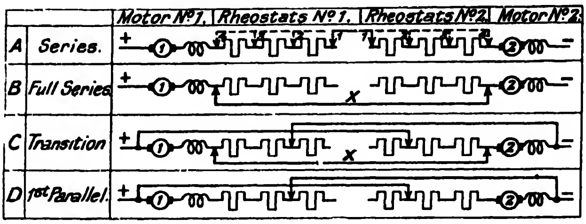


Fig. 111.—Bridge Transition.

in parallel each motor may have a rheostat connected in series with it, as shown at *B*, Fig. 109. When the motors are operating in series the two portions of the starting rheostat must be connected *between* the motors in the manner shown at *A*, Fig. 111, in which the numbered arrow-heads

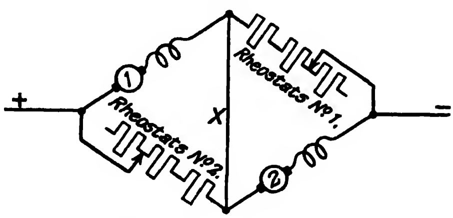


Fig. 112.—Wheatstone Network Diagram to Illustrate Bridge Transition.

indicate the order of cutting out the sections of the rheostats. At the full-series combination of the motors, *B*, a connection *X* is established directly between the motors, and the original series connection is opened, together with the short-circuiting contacts across the sections of the rheostat. At the transition step, *C*, the free ends of the rheostats are connected to the supply, so that the motors, rheostats, and connection *X* form a Wheatstone bridge network, as shown in the conventional diagram of Fig. 112. The connection *X* now forms an equalizing connection between the two parallel paths—motor No. 1 and rheostat group No. 1, motor No. 2 and rheostat group No. 2—and the opening of this connection gives the normal parallel combination of the motors, as is shown at *D*, Fig. 111. If, when transition is effected, the values of the rheostats are

such that the motor current increases to its upper limit, then the transition will have been effected under the ideal conditions shown in Fig. 108.

Bridge transition, therefore, enables the normal accelerating torque to be available from both motors throughout the whole of the starting period.

SERIES-PARALLEL CONTROLLERS

General. The various combinations of the motors and rheostats are made in the correct order by means of a controller, which, for tramway service, is usually of the drum type. This type of controller consists of a drum, or cylinder, carrying a number of insulated and inter-connected segments, which, when the drum is moved through certain angles, make

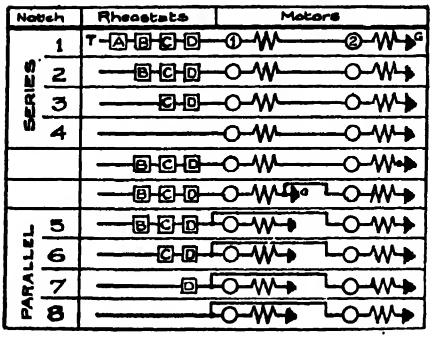


FIG. 113.

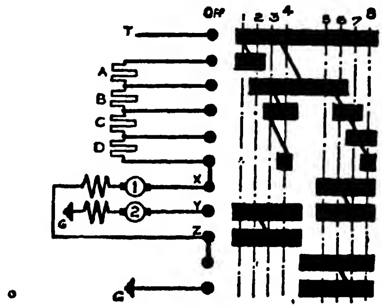


FIG. 114.

Connections, Development, and Combinations for Series-parallel Controller (Shunt transition).

contact with a number of fixed contacts (called *fingers*) to which the motors, rheostats, and supply mains are connected.

Simple series-parallel controller. The sequence of connections is shown in Fig. 113, which refers to a non-reversing controller having three rheostatic steps for each combination of the motors, shunt transition, and an earthed return for the supply system. From these diagrams the development and connection diagram, Fig. 114, is deduced.

The fingers are represented by the vertical row of large dots, and the segments by the black rectangles. The operating positions, called "notches," are indicated by the vertical chain-dotted lines (numbered 1 to 8) drawn through the segments. These lines coincide with the centre-line of the fingers in the operating positions. Thus on the first notch the top and second fingers are connected together, and the eighth and ninth fingers (from the top) are also connected. The motors are, therefore, in series and all the starting rheostat is in circuit. Sections of the rheostat are cut out on the succeeding notches, until, on the last series notch (No. 4) the motors are connected in series across the supply. Notch 4 is therefore called a *running position.* Similarly notch 8 is a running position. The other notches, 1, 2, 3, 5, 6, 7, are called *rheostatic positions.*

Observe in Fig. 114 that certain fingers (X, Z) have to be duplicated in order to obtain the series and parallel combinations of the motors

with a convenient arrangement and interconnection of the contact segments.

Observe also that the contact drum consists of three essential parts : (1) an upper part, comprising six horizontal rows of interconnected segments, which controls the cutting-out of the starting rheostat ; (2) an intermediate part comprising three rows, or two pairs, of segments—which may be all connected together—the positions of which correspond to the fingers, *X*, *Y*, *Z* ; (3) a lower part comprising two rows of segments. These three portions of the contact drum must be insulated from one another ; they will be found in all series-parallel controllers in which shunt transition is adopted.

Reversing drum. Although in practice provision must be made for operating the motors of a car in either direction of rotation from the same

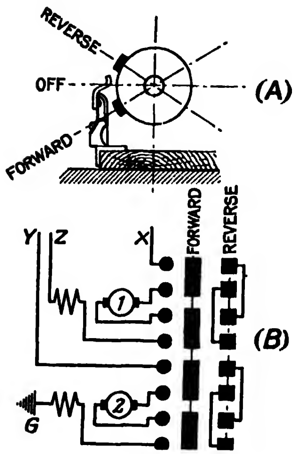


FIG. 115.—Reversing Drum.

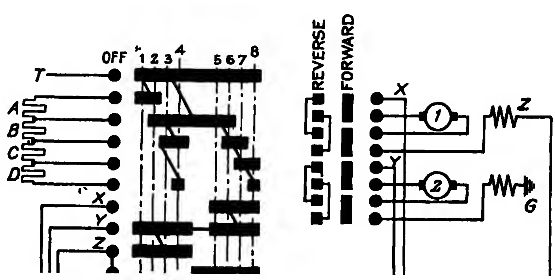


FIG. 116.—Connections of Series-parallel Controller with Reversing Drum.

controller, operation in the reverse or backward direction of the car is not required under normal running conditions. Separate contact drums and operating handles are therefore employed for (*a*) starting and speed regulation, (*b*) controlling the direction of motion. These (separate) drums are called the " power drum " and the " reversing drum " respectively. The reversing drum consists of a small contact drum and fingers for reversing the armature connections. This drum must be mechanically interlocked with the power drum so that it cannot be operated unless the latter is in the " off " position. Four fingers and two sets of interconnected contact segments are required per motor, the relative positions of fingers and segments being shown in end elevation by sketch *A*, Fig. 115, and in development by diagram *B*, Fig. 115. This diagram also shows the connections for the motors. The leads marked *X*, *Y*, *Z* in Fig. 115 are connected to fingers *X*, *Y*, *Z* in Fig. 114 in place of the connections shown in that diagram. Thus the reversing drum is supplied with power from the fingers and contacts of the power drum.

Connections of series-parallel controller with reversing drum. The

revised connections for the controller of Fig. 114, when fitted with a reversing drum (Fig. 115, *B*), are shown in Fig. 116. This diagram may be considered as representing the most elementary form of series-parallel controller for traction purposes.

Series-parallel controllers for tapped field control. In this method of control, as applied to electric traction, the motors are operated with weakened fields in the running positions of the controller, and in consequence a greater number of running speeds are obtained.

Thus, if the field windings of the motors are provided with one tapping, then four running speeds are available, viz. two speeds with the motors in series and two speeds with the motors in parallel, the two speeds in the series or parallel combinations of the motors corresponding to "full field" and "tapped field." Again, if two tappings are provided, six speeds can be obtained.

A slight modification of this method of control was adopted in the early days (about 1898) of electric traction, but was abandoned on account of the unsatisfactory performance of the motors with weakened fields.* The introduction of commutating poles, however, has enabled these difficulties to be overcome.

Field-control equipments possess several advantages over ordinary equipments, especially where the cars have to operate in congested city traffic and on outlying routes. The low speeds incidental to city traffic may be obtained economically by operating the motors with full field, and the higher speeds required for the outlying districts can be obtained by operating the motors with weakened fields. These features, and their effect on the energy consumption, are discussed in greater detail in Chapter XIX. For the present we have to consider how the additional speeds affect the connections and development of the controller.

The simplest case occurs when the weakened fields are used only when the motors are operating in parallel. In this case the series, transition, and rheostatic-parallel points of the controller are the same as those for a standard series-parallel controller. The transition from full field to tapped field is effected by short-circuiting a portion of the field winding and then cutting this portion out of circuit. If the change is effected in one operation, the motor may be subjected to a large rush of current, depending upon the point on the motor speed-curve at which the change from full field to tapped field is made, as well as on the relative field turns in circuit.

The magnitude of the rush of current may be reduced by introducing an intermediate step in the transition from full field to tapped field. Thus, instead of directly short-circuiting the section of the field winding to be cut out, a rheostat is connected in parallel with it, and the rheostat, together with the section of the winding, is finally cut out of circuit.

The connections and development of a controller for this method of control are shown in Fig. 117. It will be observed that the transition from series to parallel is effected, with full field, by short-circuiting one motor. A comparison of this diagram with that (Fig. 114) of a simple series-parallel controller will show that in each case the upper and

* The method consisted of connecting a rheostat in parallel with the field winding on the series and parallel running notches. The controllers developed by the General Electric Co. (of Schenectady) for this method of control were designated Type K2.

intermediate portions of the contact drum are similar, and the connections between the upper nine fingers are identical. The contact drum of the tapped field controller, however, requires two additional notches, and the lower portion of this drum requires seven rows of segments, instead of the two rows required in the standard controller of Fig. 114. A total of 16 fingers (and rows of segments) is required for this particular case of tapped-field series-parallel control; 11 fingers being necessary for simple series-parallel control.

In cases where the tapped field is required to be used for series running, it is necessary to change to full field before passing into the parallel notches, in order that the rheostatic acceleration on these notches may take place efficiently. Fig. 118 shows the connections of a controller

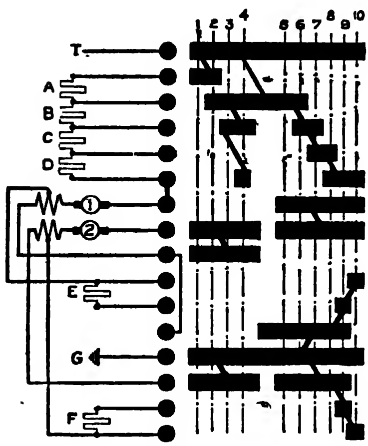


FIG. 117.

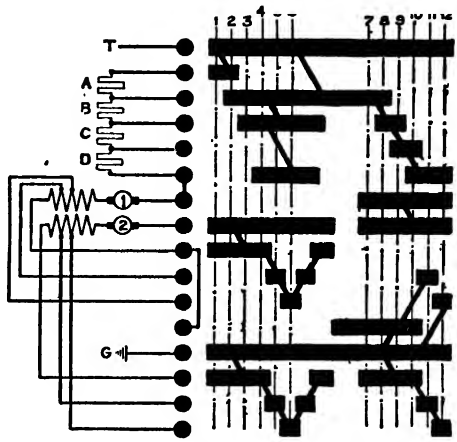


FIG. 118.

Connection and Development of Series-parallel Controllers for Tapped-field Control.

with two tapped-field positions for both combinations of the motors. In this case the change from full field to tapped field is made in a single step.

Suppression of arcing at controller contacts: Magnetic blow-out. Provision must be made in all traction controllers for the suppression of arcing at the contacts, otherwise excessive burning will occur at the fingers and segments at which circuits are opened. In all modern controllers arcing is suppressed by means of a "magnetic blow-out." A powerful magnetic field is provided at the contacts where arcing occurs, and the conditions are so arranged that the arcs are rapidly extinguished or "blown out."

The operation of the magnetic blow-out depends upon the fundamental principles of electro-magnetism that a current-carrying conductor situated in a magnetic field—the direction of which is perpendicular to the axis of the conductor—is acted upon by a force tending to move the conductor out of the field, i.e. the direction of the force is perpendicular to both the axis of the conductor and the direction of the magnetic lines.

Elementary diagrams showing the relationship between these quantities are given in Fig. 119.

The magnitude of the force is proportional to the product of current and magnetic flux density.

The magnetic field is provided by an electro-magnet, the exciting coil of which is series-wound and is connected in the main circuit of the controller, e.g. in series with one of the supply mains *T*, Fig. 114. The flux is directed to the spaces in which sparking, or arcing, occurs by a pole-piece, or a series of pole-pieces, of special design, and either a transverse or a longitudinal (axial) distribution of the flux, relative to the axis of the contact drum and fingers, is employed.

With a *transverse* distribution, the flux is perpendicular to the plane containing the contacts and the arcs are blown in an *axial*, or longitudinal, direction. For example, if in Fig. 114 the supply lead, *T*, is positive and the flux is directed inwards, perpendicularly to the plane of the paper, an arc forming between the top finger and segment will be

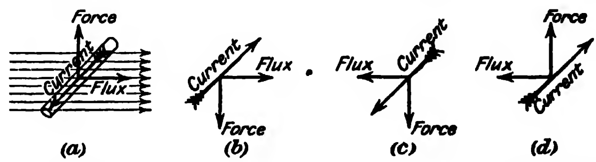


FIG. 119.—Diagrams showing Direction of Force on Current-carrying Conductor in Magnetic Field.

blown axially upwards, i.e. along the plane of the paper towards the top of the page.

If the polarity of the flux is reversed and the polarity of the supply is unaltered, the directions in which the arcs are blown will be reversed.

In order to prevent the arcs striking adjacent fingers, fireproof barriers, called "arc deflectors," are inserted horizontally between the fingers and segments.

One example of the application of this form of magnetic blow-out is shown in Fig. 120, and other examples are given later. In the controller shown in Fig. 120 the blow-out coil, *B*, is concentric with the steel shaft and is located in the cast-iron base of the controller. A lug *C*, projecting from the base, directs the flux to the swinging pole-piece *D*, from which the arc deflectors *E* are carried. The pole-piece *D* is normally held against the lug *C* by a spring latch, and therefore occupies a position parallel to the contact tips of the fingers. Hence when the blow-out coil is excited a flux is produced between the pole-piece and the shaft, and arcs forming between fingers and segments will be blown towards the arc-deflector plates.

This type of blow-out (which may be called the "shaft" type) is only suitable for controllers handling small currents, and is not adopted on tramcar controllers. It is, however, adopted on some types of master controllers for electric railways.

With an *axial* (longitudinal) blow-out field, arcs forming between fingers and segments will be blown in a direction perpendicular to the axis of the contact drum, according to the directions of current and flux. Obviously, only the radially-outward direction is permissible;

hence, in the application of this form of magnetic blow-out, special care must be taken to obtain the correct relationship between the directions of current and flux. For example, in the case of the controller of Fig. 114, if the top finger, *T*, is positive, the blow-out field at this finger must be parallel to the plane of the paper and directed towards the top of the page, while that for the second, and the remaining, rheostatic fingers must be directed towards the foot of the page, as indicated diagrammatically in Fig. 121. This diagram shows also the direction of the blow-out field for the remaining fingers and the positions in this field where consequent

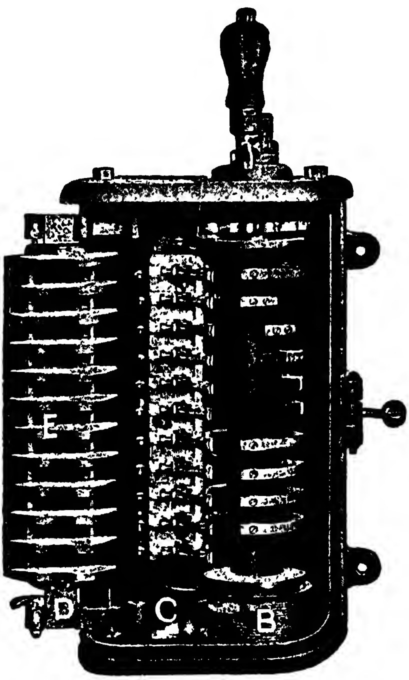


FIG. 120.- B.T.-H. Rheostatic Controller for Reversible Motor

magnetic poles must be produced in order that all arcs may be blown outwards. Examples of this form of magnetic blow-out are given later.

TRAMCAR CONTROLLERS (REQUIREMENTS AND GENERAL FEATURES)

The functions of a controller for a tramcar are (1) to control the speed of the car, (2) to control the direction of motion, and (3) to provide an electric brake, as required by statutory regulations for tramways in Great Britain. Provision must also be made for cutting-out, if necessary, a defective motor, and for operating the car (for the purpose of returning it to a depot) with the remaining motor. In some cases provision must also be made for preventing a car running backwards when stopped on a steep rising gradient.

A tramcar controller therefore differs from the controllers previously

discussed only in the provisions made for obtaining electric braking and for operating the car on one motor.

Electric braking. Since dynamo-electric machines are reversible in their functions, the motors on a car can be operated as self-excited electric generators—provided that certain conditions are satisfied—when driven by the momentum of the car. When thus driven as generators, the machines are loaded by rheostats, and the energy which is dissipated in the latter, as well as that necessary to supply the losses in the generators, is derived from the kinetic energy of the moving car. Therefore the motors on a car may be made to produce a retarding torque and to act as a brake, the braking effect being regulated by varying the amount of resistance in the load circuit. The use of the motors for braking, as well

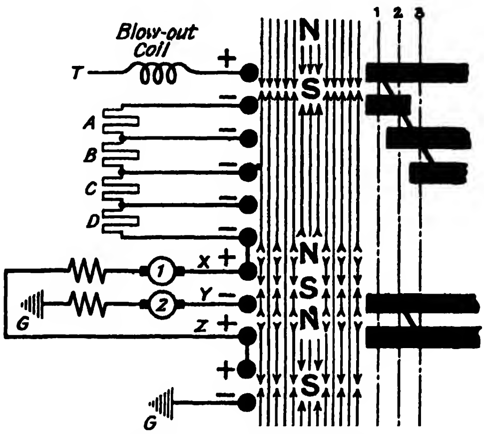


FIG. 121.—Directions of Axial Blow-out Fields for Controller of Fig. 114.

as for accelerating, purposes would, under normal service conditions, result in additional heating, and cars so operated would require larger motors than those in which the motors were used only for driving purposes. When, however, magnetic track brakes are fitted to the car, the exciting coils of the brake magnets may be connected in series with the loading rheostats, so that these magnets are excited when the motors are operating as generators. By these means additional braking is obtained, and, when the wheel brakes are also operated mechanically from the track brakes, a high retardation is obtained with relatively small output from the generators. Under these conditions the electric brake may be employed for service stops without involving excessive temperature rise or exceptionally large motors. On the larger tramway systems of this country the electrical equipment of the cars is used in this dual manner.

Conditions governing electric braking. To operate the series-wound car motors as self-excited series generators when driven by the momentum of the car, two conditions must be satisfied—

(1) The armature and field connections must be reversed relatively to each other.

(2) A rheostatic load, the maximum resistance of which does not exceed a pre-determined value, must be connected across the terminals of the machines.

The reversal of connections is necessary because, under normal braking conditions, the direction of rotation is the same as that when the car is running under power. Hence, due to the series excitation of the field winding, a reversal of the armature relatively to the field winding, or vice versa, is required in order that the machine may build-up as a generator when it is connected to a load.

The second condition, in which the maximum value of the loading resistance is specified, arises from an inherent characteristic of series generators, viz. that a generator of this type will not excite if the resistance of the load connected to its terminals exceeds a critical value.

Connections of motors for electric braking. With two-motor equipments, the motors are connected in parallel for electric braking as the series connection of the machines would produce an excessive voltage

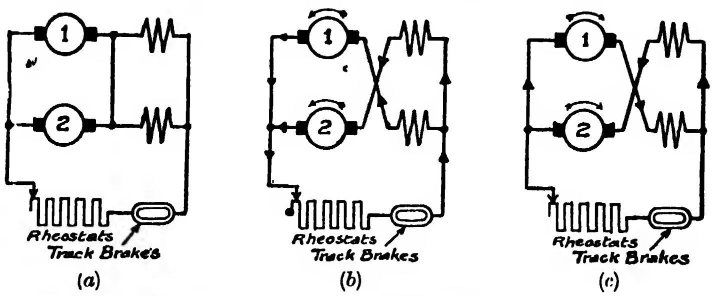


FIG. 122.—Methods of Connecting Motors for Electric Braking.

across the loading rheostats, thereby necessitating not only special insulation but rheostats of considerably higher resistance than those required for starting purposes. With the parallel connection of the motors, however, the starting rheostats, with one or two additional sections, may be utilized as loading rheostats. But in this case precautions have to be taken to ensure stable operation of the generators.

Stability in the operation of two parallel-connected series generators is obtained either by equalizing the exciting currents, e.g. by connecting the field windings in parallel, as in Fig. 122*a*, or by supplying the excitation of one machine from the armature of the other machine, and vice versa, as shown in Fig. 122*b*. Obviously the scheme of Fig. 122*b* can only be applied to *similar* machines.

The schemes of braking connections shown in Fig. 122, although being similar in their effect of giving stable operation of the generators under normal braking conditions, possess an important difference under abnormal conditions. For instance, if the direction of rotation of the generators is reversed (due to, say, a run-back) and the armature and field connections are the same as for normal braking conditions, no braking effect can be obtained with the connections of Fig. 122*a*, as the machines will fail to excite. On the other hand, an emergency braking effect will be obtained with the connections of Fig. 122*b*, as the machines will build-up in series and will be short-circuited upon themselves ; their operation being now

similar to that when two parallel-connected machines are operated without an equalizing connection, Fig. 122*c*. In order that the emergency braking effect may be obtained, it is necessary that one machine shall build-up more quickly than the other.

Again, when the equalized-field connection of Fig. 122*a* is applied to commutating-pole motors, the commutating-pole windings (which are connected in the appropriate armature circuits) and the armatures form a closed circuit. Hence, if the commutating poles are not set correctly with respect to the main poles and brushes, there is a possibility, provided that the conditions are suitable, of the machines building-up, with the commutating-pole excitation, as short-circuited series generators; this action being more marked in the event of one machine building-up more rapidly than the other. Under these circumstances very little current will pass through the external circuit, and in consequence the braking effect will be extremely small. Cases have occurred in practice where currents of over 100 amperes have been obtained in the armature circuits with only about 10 to 15 amperes in the external circuit.

These conditions cannot occur with the "crossed-field" connection of Fig. 122*b*, but in this case a defect in one motor, or a bad (high-resistance) connection in the motor circuits, will render the machines ineffective for braking purposes.* Alternatively, each machine may be braked separately, which scheme is adopted in the controller illustrated in Fig. 131.

In the event of the above conditions occurring with the equalized-field connection in practice, the braking may be improved by connecting a resistance of low value (0·5 ohm or less, according to the actual circumstances) in series with each armature. This resistance is, of course, permanently in circuit when the machines are motoring, and its value should be chosen as low as is consistent with the operating conditions.

Series-parallel controller arranged for electric braking. In controllers of this type, the control of the motors during starting and braking is effected by a single operating handle; starting and speed regulation being effected by moving the handle to one side of the "off" position (in, say, a clockwise direction), and electric braking by moving the handle to the other side of the "off" position (in, say, a counter-clockwise direction). A separate drum and handle is provided for controlling the direction of motion of the car.

The main, or operating, contact drum must, therefore, be provided with two sets of segments, viz. one set for starting and speed regulation and the other set for braking. These segments must make contact with a single line of fingers, but by suitable connections certain fingers may be used for both "power" and "brake" segments.

It has already been shown that, during braking, the motors must be operated in parallel with reversed connections and loaded on the starting rheostats. As it is impracticable to reverse the motor connections by operating the reversing drum of the controller each time braking is required,† a separate set of fingers and segments—equivalent to those of

* The first contingency is provided for in modern tramcar controllers.

† In some early types of tramcar controllers, the reversing drum was reversed mechanically (independently of the reversing handle) when the main drum was moved to the "brake" positions. This method, however, has been abandoned in favour of that described in the text.

a reversing drum—must be added to the main drum. These fingers and segments also effect the parallel connection of the motors for braking. They are arranged to break contact *after* those of the power drum, so that arcing is confined to the latter.

The connection of the generators to the loading rheostats, and the regulation of the resistance of this circuit, is effected by a set of segments which make contact with the rheostatic fingers of the power drum, an

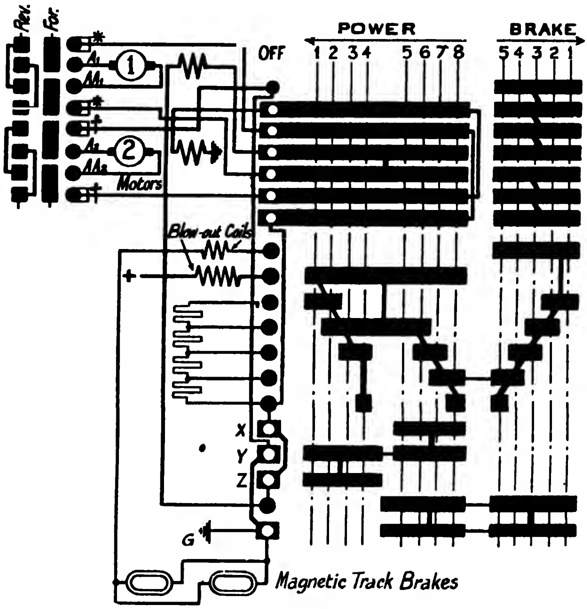


FIG. 123.—Connections of Series-parallel Controller, arranged for Electric Braking, with Run-back Preventer and Motor Cut-outs.

To cut out motor No. 1, raise fingers marked *.
To cut out motor No. 2, raise fingers marked †.

additional finger and segment being required when magnetic track brakes are used.

The complete connections of the controller are shown in Fig. 123.

Run-back preventer. It has been shown (p. 180) that with parallel-connected generators and equalized field windings (Fig. 122*a*) electric braking can only be obtained (with fixed connections) in one direction of rotation. Hence, when braking with the controller of Fig. 123, the reversing drum must be set for the direction in which the car is actually moving. This limitation is very important, in the event of a car being stopped on a steep rising gradient, for, if the car should run backwards, the electric brake will be inoperative unless the reversing handle is thrown to the " reverse " or " backward " position.

In order to provide for this contingency certain segments of the " power " side of the auxiliary drum may be extended (as in Fig. 123) so as not to break contact with the fingers in the " off " position, and by means of additional segments fitted in the " off " position of the main

drum, a short circuit is established across one motor when the drum is in the " off " position. This short-circuited motor cannot build-up as a generator when the controller is returned to the " off " position and the car is " coasting," the reversing handle being set for the direction in which the car is moving. In the event, however, of a car running backwards this motor will excite as a short-circuited generator and check the car's progress.*

The device described is called a " run-back preventer." It is a valuable adjunct to the control equipment of cars operating over hilly routes, but is, of course, only effective in the " off " position of the controller.

In cases where the motors are cross-connected for braking, as in Fig. 122*b*, the braking positions of the controller are effective for both directions of motion of the car, and may, therefore, be used for preventing a run-back.

Motor cut-out. The device for cutting-out a defective motor and enabling the car to be operated on the remaining motor may take various forms, such as—(*a*) special fingers which can be lifted from their normal positions and locked in the raised positions, thereby opening the circuits connected to these fingers ; (*b*) special double-throw switches mounted on the terminal board of the controller ; (*c*) additional segments fitted to the reversing drum and additional operating positions therefor ; (*d*) separate reversing drums (provided with additional segments for the " off " position) for each motor, and an externally-operated mechanical device for coupling either drum or both drums to the reversing handle ; (*e*) a special design of reversing drum and an externally-operated mechanical device for altering the axial position of the drum relatively to the fingers.

With devices (*c*), (*d*), (*e*), the cutting-out of a motor is effected from the outside of the controller, but with (*a*) and (*b*) the controller cover must be opened to operate the cut-out device.

Device (*a*) is the simplest in its application, as no additional fingers, segments, or wiring are necessary. Usually four fingers are fitted with locking-off cams, as indicated in Fig. 123. When operating on one motor, the series " power " positions are ineffective ; therefore the operating handle must be moved to the parallel positions to start the motor. All brake positions, however, are effective.

With device (*b*) two double-throw switches are required, but no additional fingers and segments are necessary. The wiring is such that the normal connections between the defective motor and the fingers are opened, and these fingers are connected together to complete the circuit, through the controller, to the other motor. Power is supplied to the remaining motor in the *series* positions of the operating drum, and the latter must be prevented from passing to the parallel positions by a stop which is brought into operation automatically when either cut-out switch is operated. This device is adopted in certain types of the older controllers operating in this country, and is practically a standard feature in controllers of American design.

* An electric brake, depending for its action on the motion of the car, cannot " hold " the car on an incline, although it can prevent the car from running away. Mechanical brakes are necessary for holding a car on an incline.

Cut-out devices (*c*), (*d*), (*e*) are to be found in modern British tramcar controllers.

Attention may now be re-directed to Fig. 123, which shows the connections of a series-parallel controller, arranged for electric braking, with separate reversing drum, run-back preventer, and motor cut-out device. This diagram has been built up, step by step, from elementary principles, and contains all the features necessary for a tramcar controller. The diagrams for actual modern controllers are slightly more complicated than Fig. 123, owing to the use of a larger number of " brake " positions and the adoption of an externally operated cut-out device, but

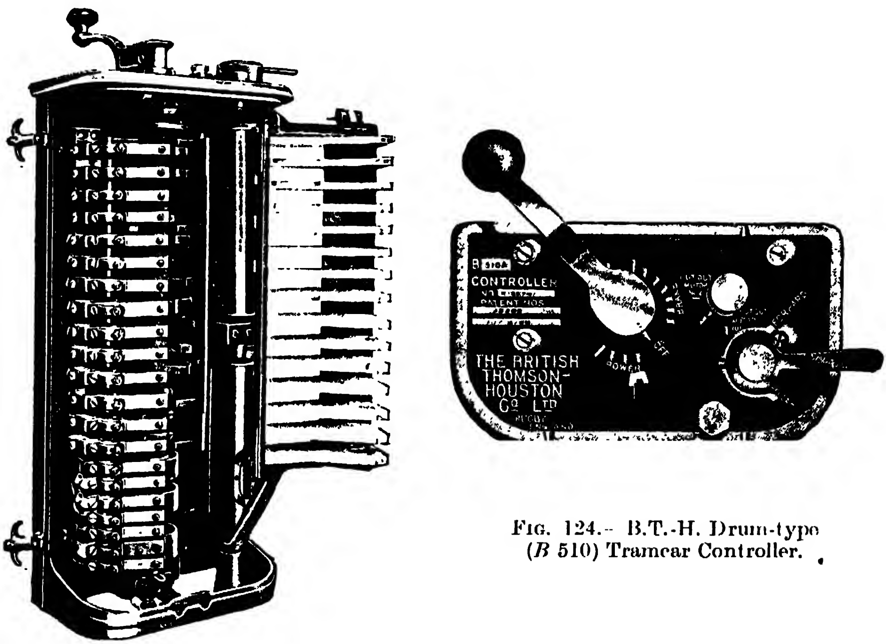


Fig. 124.—B.T.-H. Drum-type (*B* 510) Tramcar Controller.

the principles involved are the same as those discussed earlier in this chapter and applied to the controller of Fig. 123.

Examples of Modern Tramcar Controllers

B 510 controller of British Thomson-Houston Co. This controller is designed for motors having individual ratings up to 45 h.p. at 600 volts. The controller, with cover removed and arc deflector open, is illustrated in Fig. 124, and among its interesting features are : (1) the fingers and segments, (2) the magnetic blow-out, (3) the motor cut-out switch.

The fingers, Fig. 125, are of the pivoted type with renewable tips. The contact pressure is obtained from spiral compression springs which are adjustable, and flexible copper shunts connect each finger to its terminal base, so that no current is carried by either the hinge or the compression spring.

The segments are fitted to split " body castings," which are clamped

to a mica-insulated square shaft. Renewable tips are fitted to those egments subjected to arcing.

The magnetic blow-out is of the "individual-finger" type, a blow-out coil being fitted to the finger bases of each of the main fingers. Iron plates are moulded in the arc deflectors to direct the flux to the contact tips of

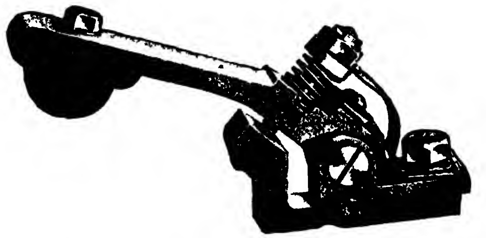


FIG. 125.—B.T.-H. Controller Finger.

the fingers. This type of blow-out closely resembles that employed with contactor-type controllers (p. 205).

The cut-out switch is of the drum type: it is located immediately below the reversing drum, and its operating spindle extends through the cap-plate as shown in Fig. 124. The cut-out spindle is operated by the

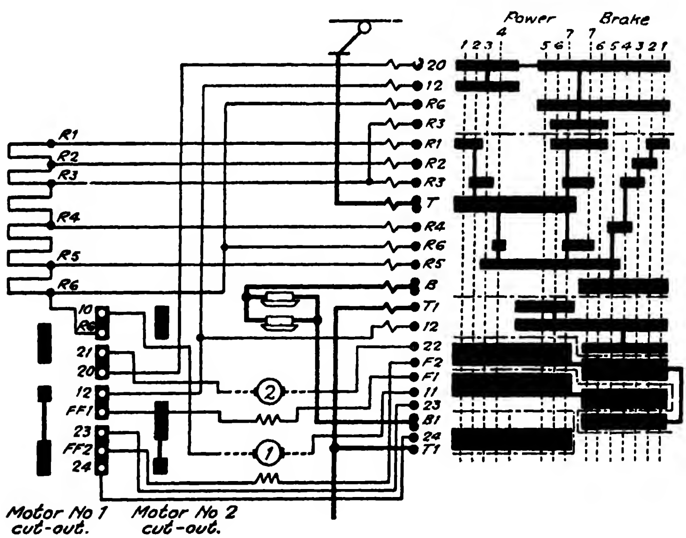


FIG. 126.—Connections of B.T.-H. Drum-type Tramcar Controller.

reversing handle, which must be removed from the spindle of the reversing drum for this purpose. The latter operation is possible only when the reversing drum is in the "off" position (i.e. when the main drum is "off," as an interlocking device between the drums ensures that the reversing drum can be moved only when the main drum is "off").

The cut-out switch has three positions, viz. both motors in circuit,

No. 1 motor cut out, No. 2 motor cut out. The connections of its nine fingers and three groups of segments are shown in the simplified diagram in Fig. 126. When this switch is in either of the "cut-out" positions an

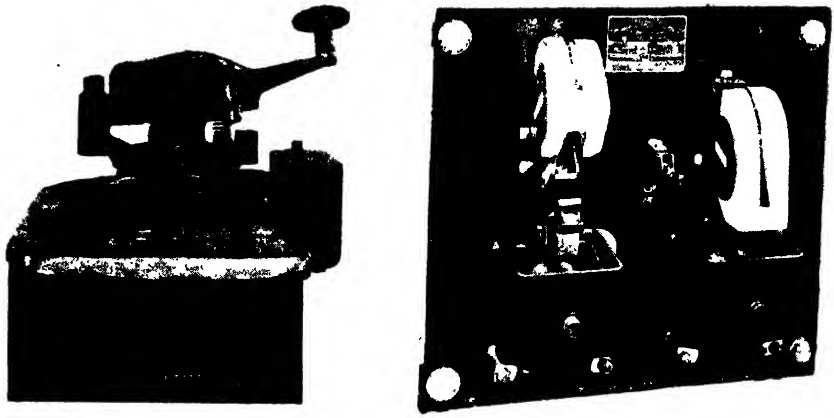


FIG. 127. -B.T.-H. Special Operating Handle and Contactors for Drum-type Tramcar Controllers.

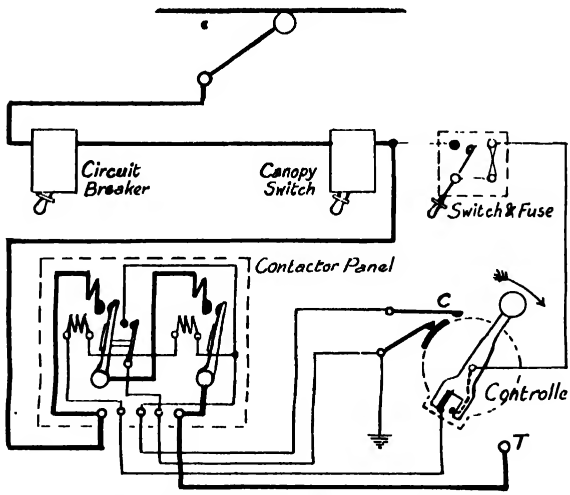


FIG. 128. Connections of B.T.-H. Operating Handle for Drum-type Tramcar Controllers.

interlocking device prevents the main drum being moved beyond the "full series" position.

A simplified diagram of connections is given in Fig. 126, in which the fingers and segments of the reversing drum are omitted, but the positions of the fingers in the armature circuits are indicated. Transition is by the shunt method (Fig. 110), and the motors are cross-connected for braking (Fig. 122 (*b*)). When either motor is cut out, electric braking can be

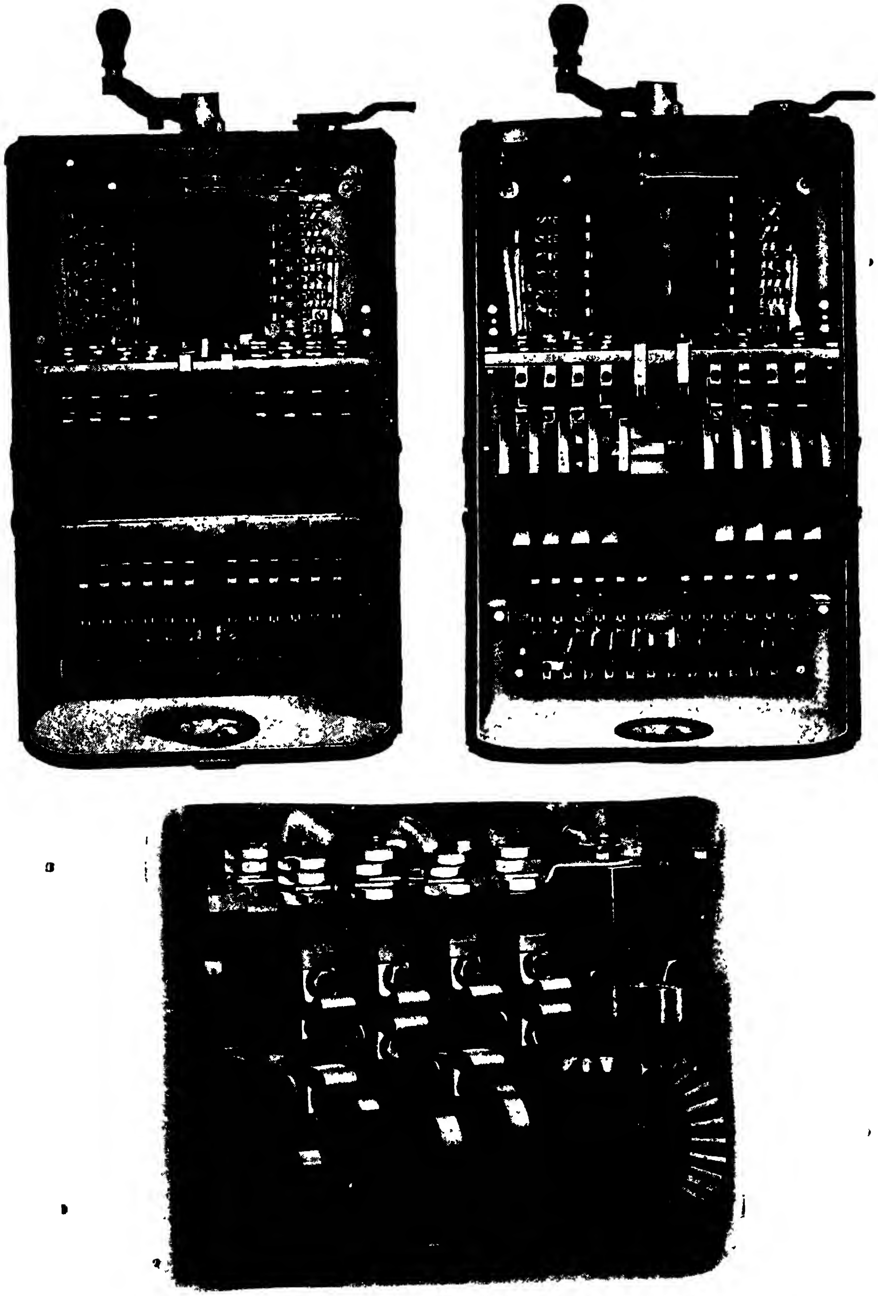


FIG. 129.--Metropolitan-Vickers Combined Contactor and Drum Type Tramcar Controller.

Views of (1) controller complete, (2) arc chute removed, (3) portion of contactors and bevel gearing.

obtained with the remaining motor, but in this case the position of the reversing handle must always correspond to the actual direction of motion of the car.

NOTE.—Further examples of drum-type tramcar controllers (including those of the Metropolitan-Vickers and English Electric Co.'s manufacture) are given in the author's *Electric Motors and Control Systems* (pp. 185–200).

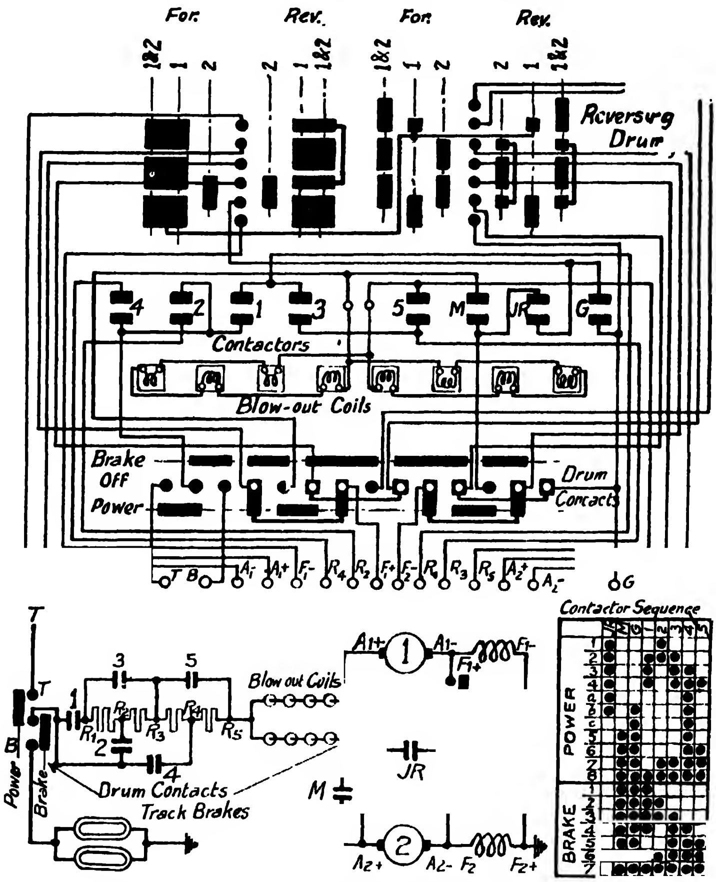


FIG. 129A.—Connections of Metropolitan-Vickers Contactor and Drum Type Tramcar Controller.

Special operating handle for controlling contactor-type circuit-breaking switches. The B 510 controller (or any other type of tramcar controller) can be fitted with a special operating handle—in place of the standard handle shown in Fig. 124—which controls a contactor-type circuit breaker external to the controller. With this special operating handle, Fig. 127, the main circuits are always broken by the contactor circuit breaker when the controller is moved to the "off" position, and in consequence the wear and maintenance of the main fingers and segments of the controller are considerably reduced (since the greatest wear is due to the

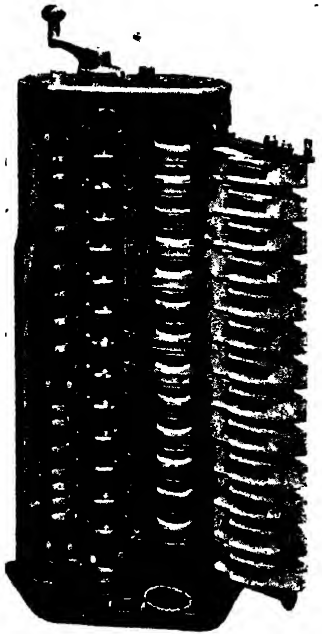


FIG. 130.—G.E.C. Cam-type Tramcar Controller.

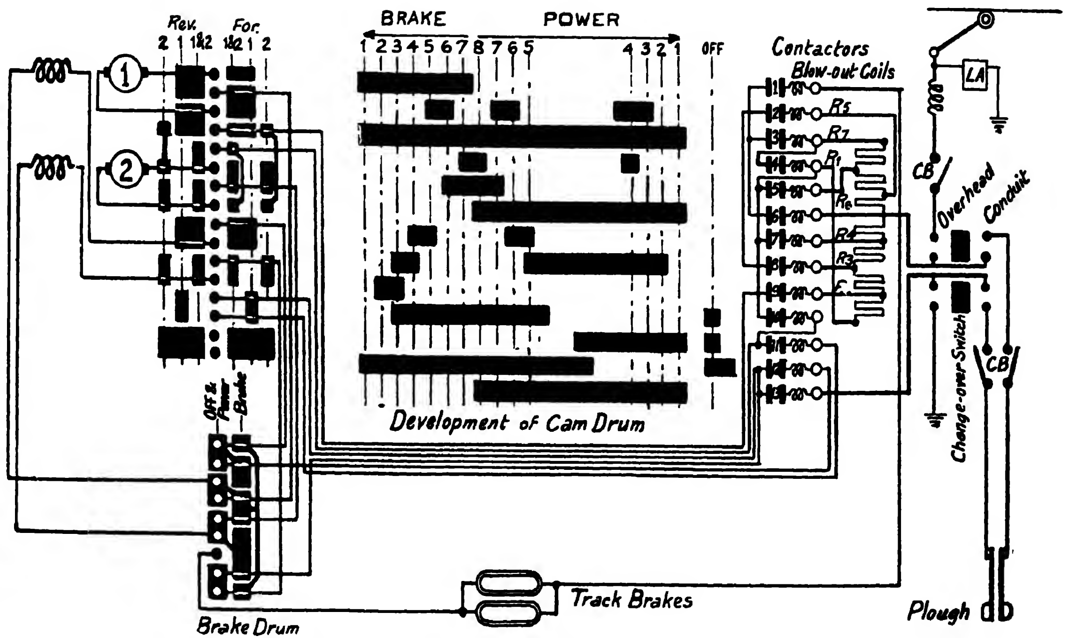


FIG. 130A.—Connections of G.E.C. Cam-type Tramcar Controller arranged for Cars Operating on both Conduit and Overhead-trolley Systems.

burning which results from arcing when circuits are broken). The handle also includes a "dead-man's" feature of such a nature that the motorman must keep the operating handle depressed while current is being supplied to the motors. If he removes his hand from the handle the circuit breakers are immediately opened.

The contactor-type circuit breaker consists of two small electromagnetic contactors mounted on a panel and located in any convenient position on the car. The main contacts are connected in series with the

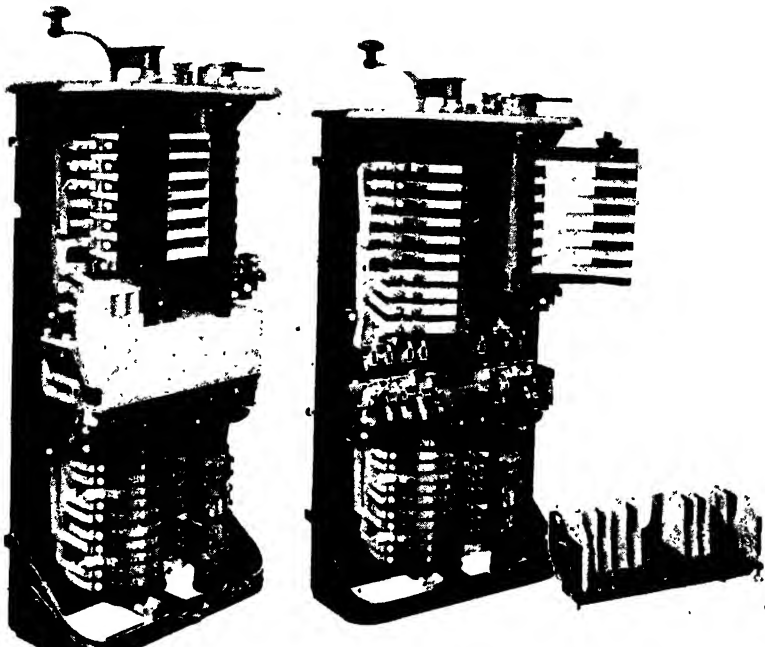


FIG. 131.—B.T.-H. Combined Contactor and Drum Type Tramcar Controller.

main supply to the controller, as shown in the connection diagram, Fig. 128. The operating coils are connected in series with an isolating switch and fuse, the contacts in the handle and an interlocking contact, *C*, Fig. 128.

The function of the interlocking contact is to prevent the re-closing of the contactors if they are opened by the release of the operating handle in any of the running positions of the controller. The interlocking is effected, in conjunction with an auxiliary circuit-closing switch on one of the contactors, in the following manner: When the controller is "off" the control circuit of the contactors is open. As soon as the controller is moved to the first "power" position the control circuit is established via the interlocking contact, provided that the "dead-man's" contact is closed (i.e. the handle is depressed). When the contactors close, the

interlocking contact is short-circuited by the circuit-closing auxiliary switch, and therefore the contactors remain closed when the interlocking contact is broken by moving controller to second and following notches.

If the handle is moved towards the "off" position the control circuit is immediately interrupted at the contact in the handle. The main circuit

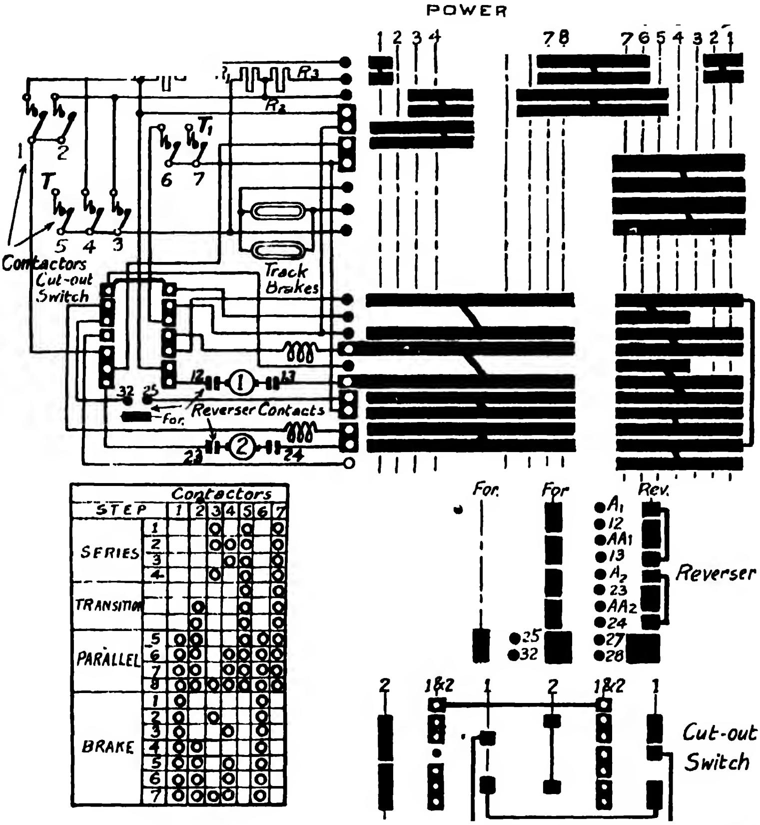


FIG. 131A.—Connections of B.T.-H. Combined Contactor and Drum Type Tramcar Controller.

is, therefore, broken by the contactors before the main drum of the controller has moved.

Combined drum and cam-shaft contactor controllers. Controllers of this type have recently been developed to meet the severest tramway service conditions. Views of a Metropolitan-Vickers controller are shown in Fig. 129, and a diagram of connections is shown in Fig. 129A.

The controller consists of a combined reversing and cut-out drum (which is centrally placed in the upper part of the case and is operated through linkwork by the reversing handle); a group of eight cam-operated contactors; and a group of fingers (arranged horizontally at the lower part of the case) with a corresponding contact quadrant, which is mechanically connected with the camshaft. These fingers and

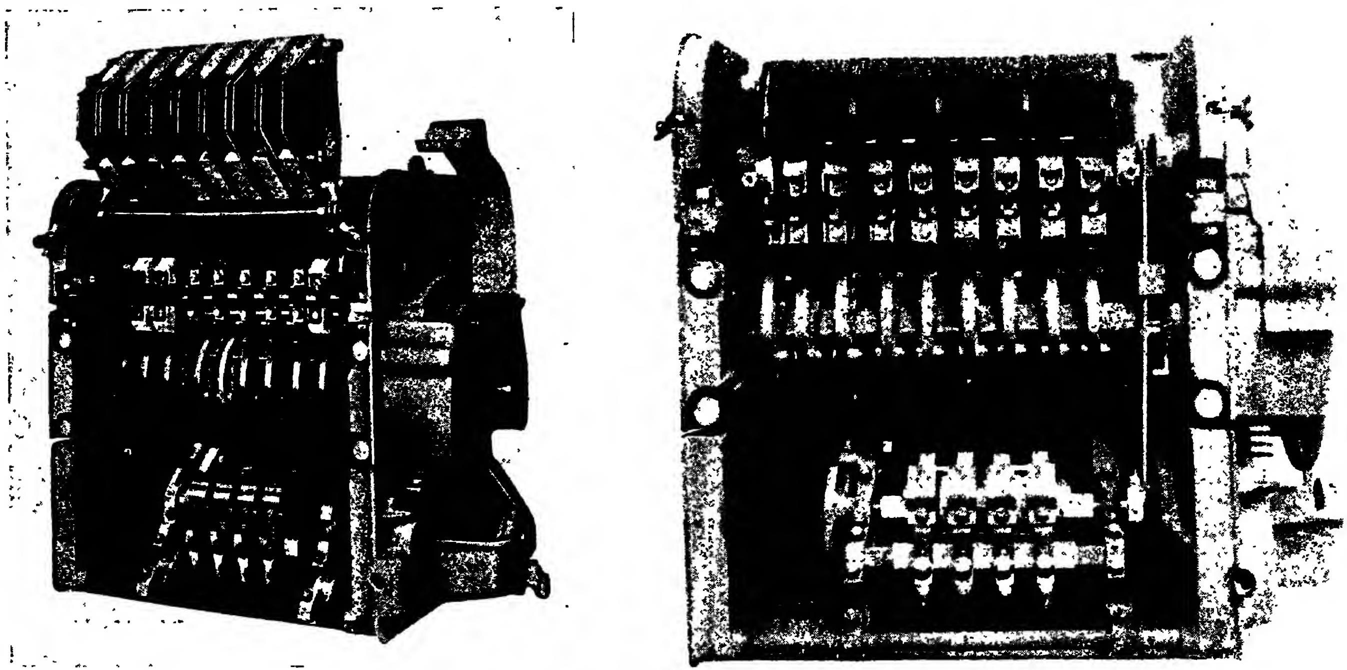


FIG. 132.—English-Electric Trolley-bus Controller.

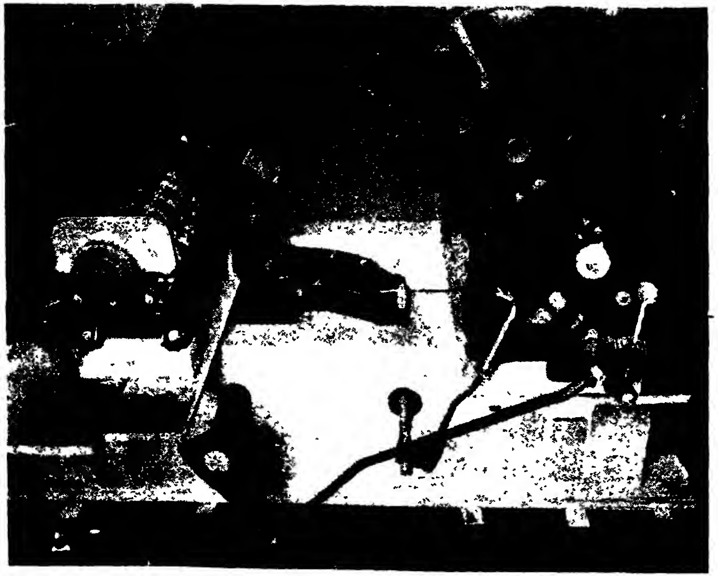


FIG. 132A.—English-Electric Trolley-bus Controller with Operating Levers in Position.

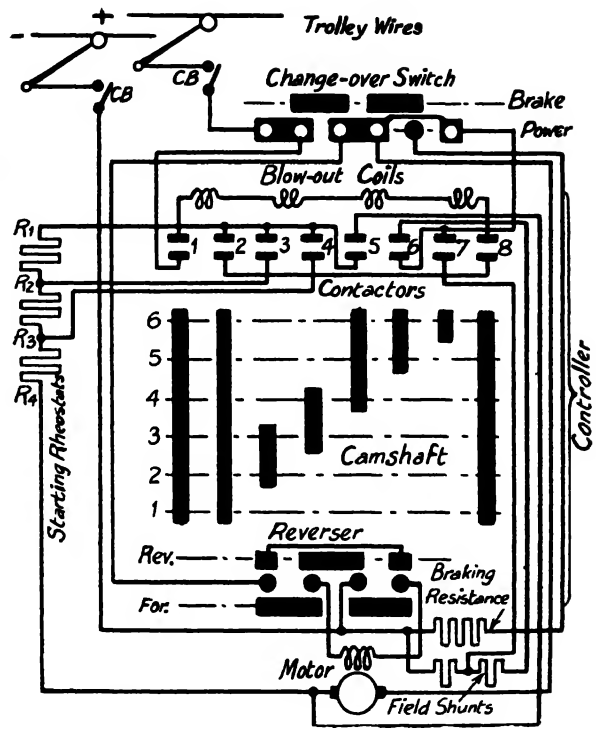


FIG. 132B.—Connections of English-Electric Trolley-bus Controller.

segments form a change-over switch for effecting the change of connections between power and braking. The quadrant has three positions, viz. "power," "off," "brake": it is operated by a cam mechanism from the camshaft which actuates the contactors, and is locked in each position. Moreover, this quadrant is moved only when all the contactors are open (i.e. when the main circuits are open).

The main operating handle is connected to a central shaft—on which the reversing drum is loosely mounted—the lower end of which terminates in a bevel wheel which engages with a corresponding wheel fixed to the camshaft, as shown in the detail view in Fig. 129.

Each of the contactors consists of a fixed contact, which is provided with an individual magnetic blow-out, and a hinged moving contact, which is fitted with a roller and a compression spring. In the "off" position of the controller the rollers are off the cams, and the moving contacts are maintained in the "off" position by the action of the springs. When an appropriate cam engages the roller of a contactor, the moving contact is lifted and the contactor is closed against the action of the spring, as shown in the detail view of Fig. 129. A wiping action occurs at the contact during closing, the object of which is to ensure that the circuit is made and broken at the contact tips so that any burning of the tips due to arcing shall not damage the contact faces.

Each contactor is provided with a separate arc chute and a powerful magnetic blow-out, so that arcing is effectively suppressed. In consequence of this feature and the rapid opening of the contactor, due to the spring, arcing at the contacts is effectively suppressed. (It is, of course, due to these features that contactors possess such a great advantage over drum-type controllers for large currents.)

A General Electric controller is illustrated in Fig. 130, and a diagram of connections is shown in Fig. 130A. In this controller the camshaft is vertical and arranged centrally. The thirteen contactors—each of which is fitted with a blow-out coil—are located at the right-hand side of the camshaft. The combined reversing and cut-out drum, together with the change-over (brake) drum, are located at the left-hand side of the camshaft. The reversing drum is operated, through linkwork, from a knob located in the cap-plate on the right-hand side of the main operating handle, but the cut-out device is operated from a knob on the left-hand side of this handle. The change-over (brake) drum is actuated by a cam fixed to the camshaft.

The thirteen contactors are built as a complete unit and are assembled on twin mica-insulated rods clamped to the controller back. The cams are insulated from the camshaft, which is mounted in ball bearings and is fitted with a non-removable handle.

The blow-out coils are provided with steel cores, which, when the arc deflectors are closed, are connected to steel plates embodied in the arc deflector plates.

The cut-out knob is so connected to the linkwork of the reversing drum that the angular movement of this drum, corresponding to the movement of the reversing knob and handle, is dependent upon the position of the cut-out knob; e.g. when the cut-out knob is in either of the "cut-out" positions the throwing of the reversing handle to an

operating position moves the reversing drum to the corresponding cut-out position indicated in Fig. 130A.

The B.T.-H. controller, with cover and arc deflectors removed, is illustrated in Fig. 131. It consists of a main contact drum, a reversing drum, a drum-type motor cut-out switch, and a group of seven cam-operated contactors. The fingers and segments of the main drum possess

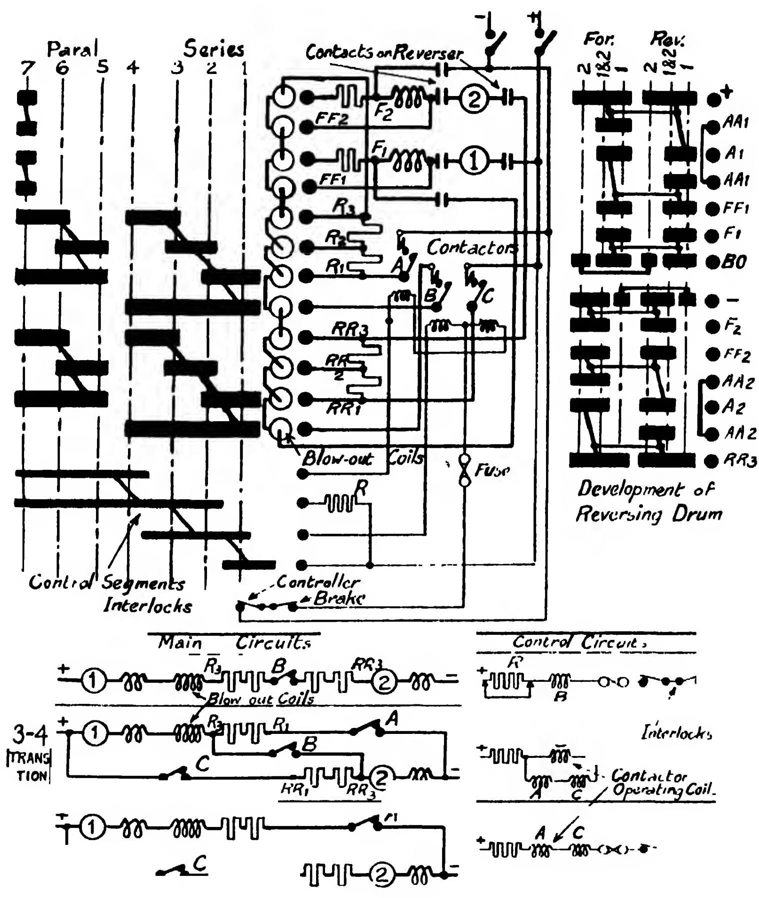


FIG. 133.—Connections and Development of Ransomes, Sims & Jefferies and Electro-Mechanical Brake Co.'s Series-parallel Controller for Twin-motor Trolley-bus.

features similar to those mentioned in connection with the B 510 controller. The reversing drum and motor cut-out switch occupy the upper and lower right-hand positions respectively in Fig. 131, and are operated in the same manner as those of the B 510 controller.

The main handle operates the main contact drum in the same manner as in a standard controller and is also geared, through skew gearing, to a horizontal shaft, to which seven cams are fitted. The cams are insulated

from the shaft and operate the moving contacts of the contactors by means of rollers.

The contactors are connected in the power and braking circuits as shown in the simplified diagram of connections, Fig. 131A. A study of this diagram will show that (1) transition is by the shunt method, (2) one

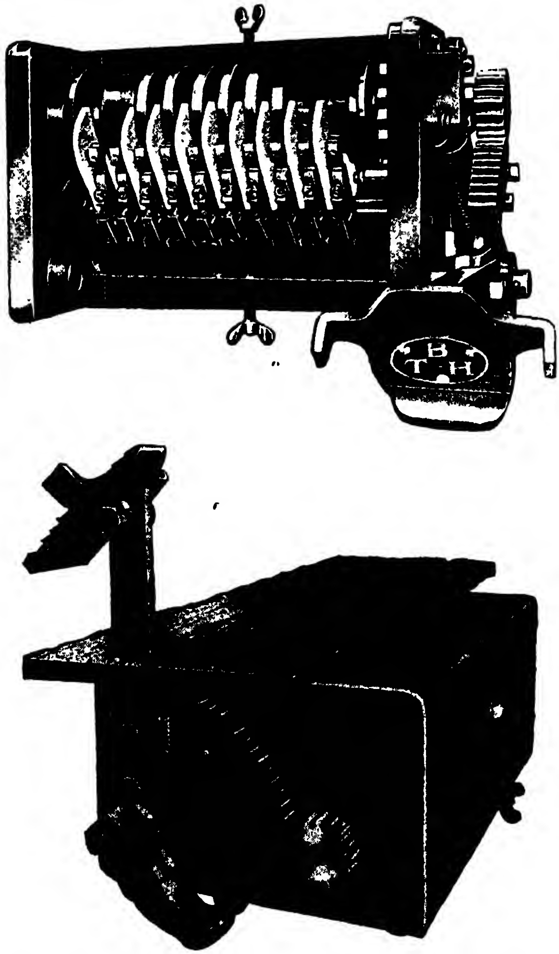


FIG. 134. B.T.-H. Master Controller for Trolley-bus.

motor is short-circuited in the "off" position of the main drum, (3) the motors are cross-connected for the first three braking positions, and (4) each motor is braked separately for the remaining braking positions.*

TROLLEY-BUS CONTROLLERS

Controllers for trolley buses are usually of the pedal- or foot-operated type, in order that the driver may have both hands available for steering

* Separate braking of each motor has been found desirable in practice with commutating-pole machines. See page, 181.

and applications of the hand brake. In all cases a hand-operated reversing switch is employed which is interlocked, either mechanically or electrically, with the main controller so that the former can only be operated when power has been cut off. Usually no provision is made for service electric braking, as the vehicles are equipped with both foot- and hand-operated brakes and, in some cases, compressed-air brakes (controlled by a foot-operated valve) are provided in addition. With single-motor equipments, however, arrangements are usually made for emergency electric braking.

With two-motor equipments, or their equivalent, the controller is of the series-parallel type and is usually fitted with a cut-out switch to

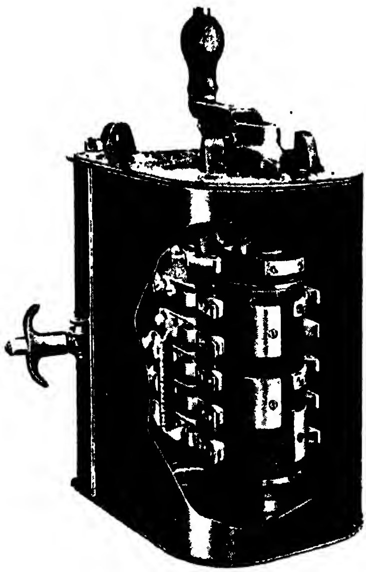


Fig. 135. B.T.-H. Hand-operated Reverser for Trolley-bus Control Equipment.

enable the vehicle to be operated on one motor in the event of the other motor becoming disabled.

On account of the limited space available for the controller and the special method of operation, the construction differs in many respects from that of a standard tramcar controller. Moreover, as the controller has to be mounted horizontally, at floor level, in a rather awkward position for carrying out inspections and adjustments, the maintenance must be kept low.

In some cases individual electro-magnetic contactors are employed for the motor circuits, and the pedal-operated controller has then only to handle the small operating current of the contactors. This form of remote control resembles that employed in electric railway traction and is discussed fully in the following chapter. For the trolley bus, remote control possesses the advantages over direct control that (1) the master

controller is smaller, (2) it requires less force to operate, (3) the maintenance is less than that of a pedal-operated main controller, and (4) the contactors can be mounted in a position convenient for inspection.

Example of pedal-operated controller for single-motor vehicle. Views of an English-Electric controller, operating on the camshaft contactor principle, are shown in Fig. 132. The controller is constructed on the "unit" principle, and any of the principal parts can be easily removed by withdrawing four bolts. The top "unit" includes the contactors and

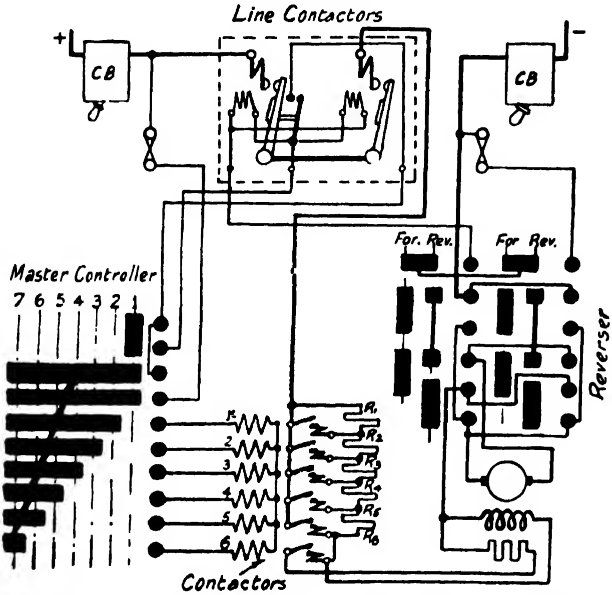


FIG. 13 Connections of Master Controller, Contactors, and verser for B.T.-H. Single-motor Trolley-bus Equipments.

blow-out coils; the central unit the camshaft, and the bottom "unit" is the reverser.

The camshaft is ratchet-driven from a pedal, which is connected through linkwork to the operating mechanism, as shown in Fig. 132A.

Provision is made for rheostatic braking, a separate change-over switch, shown in front of the pedals in Fig. 132A, being provided for changing the connections (Fig. 132B). The first four steps of the camshaft controller control the braking torque.

Example of pedal-operated series-parallel controller. This controller (which was developed for Messrs. Ransomes, Sims & Jefferies' twin-motor vehicles) is of the drum type, and is used in conjunction with three electro-magnetic contactors; such a combination possessing the advantages that all serious arcing may be confined to the contactors, and that bridge transition may be employed with a simple arrangement of fingers and segments in the controller. The simplicity of the main contact drum can be seen from the connection and development diagram, Fig. 133.

The controller consists of a pedal-operated ratchet-driven main drum,

and a hand-operated reversing drum, which is fitted with a device to enable either motor to be cut out if necessary. The two drums are mechanically interlocked in a manner similar to those of a tramcar controller. Moreover, when either motor is cut out the main drum cannot be moved beyond the third (full series) notch. The method of operating the main drum is as follows—

When the reversing lever has been set for the required direction of motion, the foot pedal is fully depressed, which moves the main drum forward one notch. The pedal is released a certain amount and again

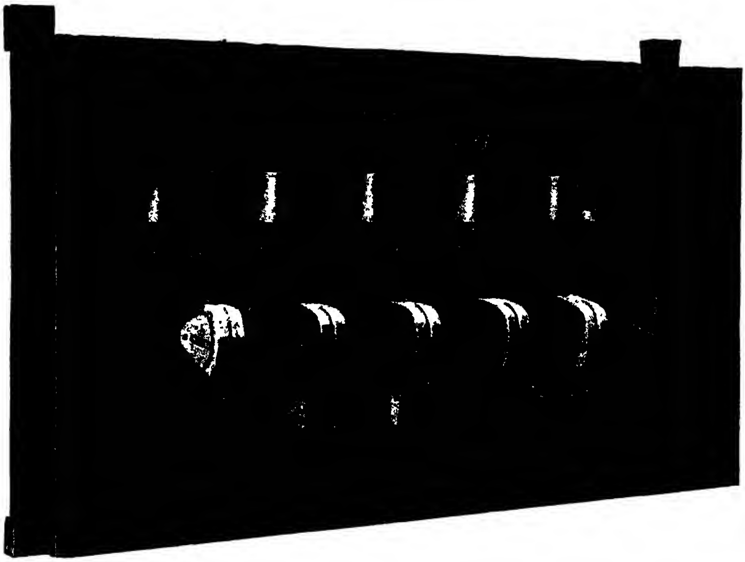


FIG. 137.—B.T.-H. Contactor Group for Control of Twin-motor Trolley-buses.
[Dimensions—36½" × 24" × 9".]

depressed, which moves the drum to the second notch. Succeeding notches are obtained in the same manner. The full release of the pedal causes the drum to return to the "off" position, and at the same time opens an interlocking contact which is in series with the operating coils of the contactors. This circuit is opened before the drum returns to the "off" position, and therefore the circuit is broken by the contactors.

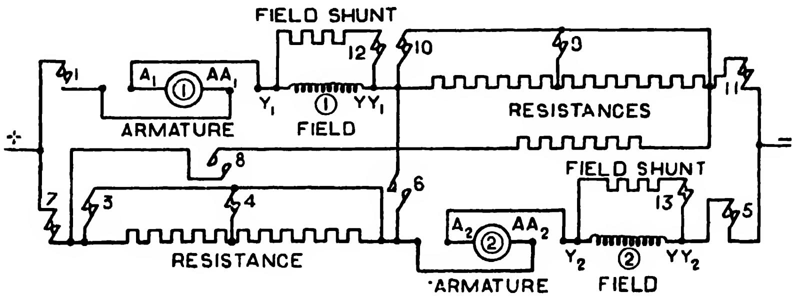
The contactors are controlled by four fingers and a set of segments connected to the main drum of the controller. Two interlocks are included in the control circuit: one is actuated by the brakes and opens the control circuit when the brakes are applied; the other is actuated by the pedal and opens the control circuit when the pedal is fully released.

The controller has seven operating positions, viz., three series (two of which are "rheostatic" steps) and four parallel (two of which are "rheostatic" steps, and two are "full-parallel" steps, one (No. 7) being a shunted field step.

Transition is effected entirely by the contactors in the following manner—

The contacts of the "series" contactor, B, are first transferred by means of contacts on the main drum, from the inner ends, R_1, RR_1, of the starting rheostats to the outer ends R, R_3R_3; so that this contactor forms a direct series connection between the motors, and corresponds to connection X, Fig. 111. Contactors A and C are then closed, thus forming the "bridge" network. Finally, contactor B is opened.

Example of contactor-type (remote) control. The control equipment comprises: a pedal-operated master controller, a hand-operated reverser, and a group of electro-magnetic contactors (which includes a pair of main circuit-breaking or "line" contactors and a number of contactors



	POINTS	CONTACTORS											
		1	3	4	5	6	7	8	9	10	11	12	13
SERIES	1	●			●			●					
	2	●		●	●			●					
	3	●		●	●			●	●				
	4	●	●	●	●			●	●				
	5	●	●	●	●			●	●	●			
	6	●			●	●							
PARALLEL	7	●			●		●				●		
	8	●		●	●		●		●		●		
	9	●	●	●	●		●		●		●		
	10	●	●	●	●		●		●	●	●		
	11	●	●	●	●		●		●	●	●	●	●

FIG. 138. Main-circuit Connections (simplified) for B.T.-H. Contactor Equipment for Twin-motor Trolley-buses.

for cutting-out the sections of the starting rheostat and for effecting the combinations of the motors).

Fig. 134 shows a typical master controller, Fig. 135 shows a hand-operated reverser, and Fig. 137 shows a group of contactors for the control of a two-motor vehicle.

A simplified diagram of connections for a single-motor equipment is given in Fig. 136, in which the electrical interlocking of the master controller, reverser, and "line" contactors should be observed. This interlocking ensures that the line contactors can be closed only when (*a*) the reverser is set for the desired direction of motion of the vehicle, and (*b*) the master controller is in the first position.

The master controller is of relatively small dimensions. It may be so arranged that when the pedal is depressed against the return spring the controller is moved to *either* the "on" positions or the "off" position. In the latter case the controller is normally in the "full-on" position, and

the pedal must be depressed to the first operating position to obtain current in the motor circuit, after which it is released to the full-on position to obtain full speed.

When the controller is arranged for shunted-field operation a definite stop is provided at the full-field running points in both the series and parallel combinations with two-motor equipments. Hence the controller cannot be notched up to a shunted-field position without a pause being made in the preceding full-field running position.

When emergency electric braking is required, additional notches are provided on the reverser. These notches connect the motor as a series generator to the starting rheostats (as load), the latter being cut out in a number of steps. To obtain electric braking the reverser must be thrown to these positions in the opposite direction in which the vehicle is moving, this operation cutting off power from the contactors. The braking is regulated entirely by the reverser, the master controller and contactors being completely ineffective, owing to the control circuit being interrupted at the interlocking contacts in the reverser.

Fig. 138 shows the main-circuit connections for the series-parallel control of a two-motor vehicle, bridge transition being employed. Twelve contactors are required for the eleven operating points. of which three are "running" points, viz., No. 6 (series), No. 10 (parallel, full fields), No. 11 (parallel, shunted fields). Transition, which takes place between the sixth and seventh points, is effected by closing contactors Nos. 7 and 11 and opening No. 6 ; Nos. 1 and 5 remaining closed.

CHAPTER IX

THE CONTROL OF DIRECT-CURRENT RAILWAY MOTORS

ELECTRIC trains for suburban service are usually made up of a number of motor and trailer coaches, and the composition of the train is altered to suit the traffic. Thus for light traffic one motor-coach and one trailer may be sufficient, while for heavy traffic two or more motor-coaches and a number of trailers may be required. Each motor-coach may be equipped with two or four motors, but all of the motors throughout the train must be controlled simultaneously from one point.

Direct control. Where two motor-coaches are used, the control may be carried out in a manner similar to that adopted on tramcars by arranging the motor-coaches at the ends of the train and equipping each with a controller capable of controlling all the motors. With this type of control (called the "**direct control**" **system**) the whole of the power must pass through the controller at the driving end of the train. If the reversing is done at the controller, a large number of train cables will be required, even if only two motors are used on each motor-coach, and the majority of these cables must be of heavy cross-section. If, however, a remote controlled electrically operated reversing switch is used for each motor, the heavy train cables may be reduced to a minimum of four, but to obtain this result the starting rheostats must be duplicated on each motor-coach (i.e. each motor-coach is equipped with starting rheostats for its own motors and also for the motors on the other motor-coach, only one set of rheostats being in use at once).

This system—with remote-controlled reversers and duplicated starting rheostats—was developed by Messrs. Dick, Kerr & Co. (now the English Electric Co.) for the original motor-coach trains on the Liverpool-Southport section of the London, Midland and Scottish Railway. Further details are given in the author's *Electric Motors and Control Systems*, pp. 201–205.

Multiple-unit control. The direct system of control, while giving a certain degree of flexibility to the composition of the train, limits the heaviest train to that which can be handled by two motor-coaches. To obtain greater flexibility an indirect method of control—known as the **multiple-unit system**—has been developed. In this system each group of two or four motors is provided with a series-parallel controller, a reverser, starting rheostats, and current-collecting gear, and is considered as *one unit* of the train equipment. The motor-controller and reverser of each unit are operated electrically and remote controlled from a master-controller, which supplies current to the control circuit of the motor-controller. The simultaneous control of any number of motor-controllers is obtained by connecting their control circuits in parallel. The motor circuits are quite separate from the control circuit, and are not inter-connected, except by the current-collecting gear.

Master controllers, connected in parallel, may be located at different parts of the train, but only one of these is in use at a time. Current is

supplied to the control circuits through the master controller at the driving end of the train, and is conducted to the various motor-controllers by a multiple-conductor cable.

With this system of control the maximum flexibility in the composition of the train is obtained, since, so far as the control is concerned, the maximum number of motor-coaches is limited only by the current-carrying capacity of the master controller and the control-circuit cable. Usually, however, the length and weight of the train are the limiting conditions. A further advantage is that the master controllers occupy very little cab space, and the motor-controllers may be located underneath the coaches.

The multiple-unit system of train control has received its greatest development in the United States of America from the General Electric Co. (Schenectady) and Westinghouse Co. In that country the system is used on an extensive scale, and, in fact, has entirely superseded large controllers. Multiple-unit systems have also been developed by the principal British and Continental manufacturers of traction equipment.

Classification and application of multiple-unit systems. Multiple-unit systems are *classified* according to the system of operation and the type of motor-controller. Thus the motor-controller may be operated either entirely electrically (called "**all electric**" operation), or by pneumatic cylinders having electrically-operated control valves (called "**electro-pneumatic**" operation). Again, the motor-controller may consist either of a number of individual switches (called "**unit switches**" or "**contactors**") each having its own operating mechanism and being self-contained, or, alternatively, a group of switches or contactors may be operated by cams mounted on a common shaft, so that only a single operating mechanism is required for the switch group. Motor-controllers of the former type are called **unit-switch controllers,** or **individual-contactor controllers**; those of the latter type are called **cam-shaft controllers.**

Further, with a power-operated motor-controller two methods of notching-up, or progression from step to step, are possible, viz. (1) synchronously with the movements of the master controller (and therefore under the direct control of the motorman just as if a hand-operated motor-controller were in use), (2) automatically, the notching-up, when once started by the motorman, being completed automatically (by means of relays and auxiliary switches) without further effort or skill being necessary on the part of the motorman.

Application. The all-electric individual-contactor system has a very extensive application in this country, America, the Continent, and other parts of the world where railways have been electrified on the direct-current system.

The electro-pneumatic unit-switch system was developed originally by the Westinghouse Companies, and its principal applications are to be found in America. The system has also received development from a number of Continental firms, and many applications are to be found in Europe. In this country the system has been adapted to British railway practice by the Metropolitan-Vickers Electrical Co. (formerly the British Westinghouse Co.), and is in operation on the Metropolitan Railway, London.

The cam-shaft motor-controller systems represent the latest development in multiple-unit control. The system with electro-pneumatic operation was developed originally in America by the General Electric Co., and that with all-electric operation was developed in this country by the English Electric Co. Both systems have large applications in modern electrifications.

Previous to the development of the electro-pneumatic cam-shaft controller the Westinghouse Co. had, in the early days of electric traction, applied electro-pneumatic operation to ordinary drum-type series-parallel controllers to adapt them to multiple-unit operation. (Such controllers are still in service on the Mersey Railway.) The electro-pneumatic drum controller was subsequently abandoned in favour of the electro-pneumatic unit-switch controller. In recent years, however, the Westinghouse Co. have developed a combined electro-pneumatic unit-switch and drum controller in which contactors are employed for the operations connected with the grouping of the motors, and a drum controller is employed for cutting-out the sections of the starting rheostats.

We shall now consider the contactor and cam-shaft systems more in detail.

All-Electric Multiple-Unit Contactor System for 600-Volt Circuits

The equipment which is necessary on a *motor-coach* for control purposes comprises—

Master controller, series-parallel motor-controller (with rheostats and reverser), control-circuit multi-core cable (control bus-line) with coupler sockets, current-limit relay (for automatic control only), field-tapping relay (for tapped-field control only).

That necessary on a *trailer coach* comprises—

Master controller (when required), control-circuit multi-core cable with coupler sockets.

To ensure protection of the equipment against overloads, and to isolate, when necessary, the control apparatus of any motor-coach from the control bus-line, each motor-coach is further equipped with—

Automatic circuit breaker with electrical reset, control switch for circuit breaker, isolating switch for master controller, cut-out switch and fuses for isolating the control circuit of the motor controller from the control bus-line.

A diagram is given in Fig. 139 to show the layout of the apparatus and the method of connections for a motor-coach equipped with two motors and intended for single-end operation. It will be observed that branch connections from the control bus-line and also from the main bus-line (the object of which is to interconnect the collector shoes on the several motor-coaches of a train) are made by means of special connection boxes. The possibility of faults in these cables due to bad jointing is, therefore, eliminated. The fuses shown in the main circuit are of the magnetic blow-out type and are intended to give protection against short circuits.

Contactors. A group of from 12 to 14 contactors form the series-parallel motor-controller. The contactors are assembled in a common

frame for mounting either under the car (in which case suitable covers are provided) or in a compartment adjoining the driver's cab.

Each contactor consists essentially of (*a*) two contacts, one being fixed and the other movable; (*b*) a plunger-type electromagnet for operating the moving contact; (*c*) a magnetic blow-out. Typical modern contactors are illustrated in Fig. 140. Referring to illustration (*a*), the plunger *P* is connected by the pin *D* to the double lever *A*, *B*, which is hinged to the frame at *C*. The lever *B* carries the moving contact and is connected to *A* by both a pin joint, *E*, and compression springs, *S*.

The **fixed contact** is arranged vertically above the moving contact in the arc chute *G*, and is connected, through a blow-out coil, to the terminal *T*. The magnetic circuit of the **blow-out coil** is formed by an iron

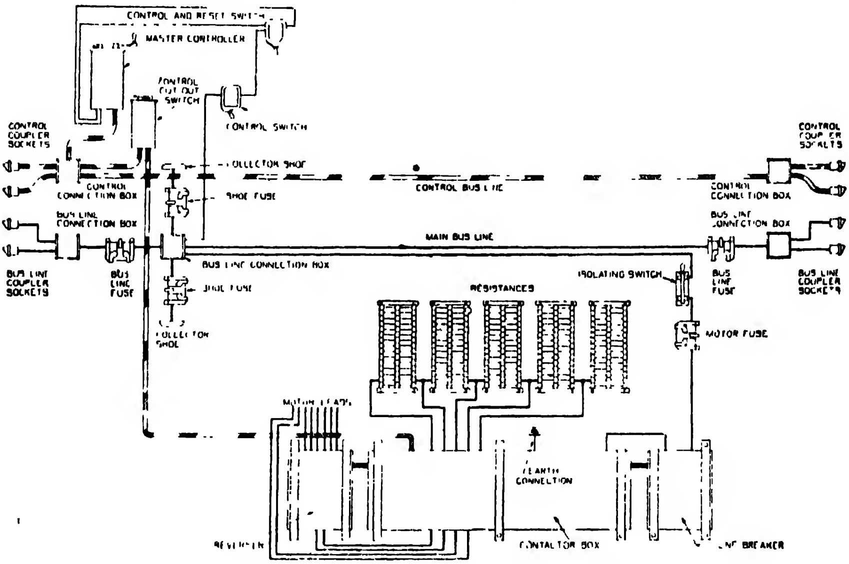


FIG. 139.—Layout of Control Apparatus on Motor-coach of Multiple-unit Train.

core and two pole-pieces, one of which is shown at *H*. The pole-pieces are designed to produce a strong magnetic field in the vicinity of the main contacts, and the latter are fitted with curved horns to provide a definite path for the arc. In this manner the arc is confined to the centre of the arc-chute, and heavy currents may be broken successfully.

An important feature in the operation of the contactor is the rolling or "**wiping**" **action** which takes place at the contacts when the contactor closes. This action is brought about by the springs *S* as follows: When the plunger is lifted, the double lever *A*, *B* moves about the fulcrum *C* until the contact tips touch. The vertical motion of the outer end of the contact-lever *B* is then arrested, and, since the plunger has not completed its stroke, further vertical motion of *B* can only take place at the hinge *E*. The flexible link formed by the springs *S* allows this motion to occur at *E*, and, at the same time, the moving contact rolls on the fixed contact, so that the contacts are brought together. In opening, the

reverse action takes place, and therefore arcing can only occur at the contact tips. The springs also provide the necessary pressure between the contacts and force the contact arm to move rapidly when the circuit of the operating coil is interrupted.

The **operating coil** *J* is wound with sufficient turns to ensure satisfactory operation at one-half of the normal operating voltage. The normal operating current is about 1 ampere.

To prevent incorrect operation of the contactors the operating coils are **electrically interlocked** by means of auxiliary contacts controlled by the plunger. The auxiliary contacts are arranged at the back of the contactor and the circuit is opened or closed by means of a moving contact operated through linkwork from the plunger.

All small wiring between the contactors forming a series-parallel controller is brought to a terminal board from which connections are made to the control bus-line cable.

The operating mechanism of the **G.E.C. contactor,** Fig. 140 *b*, differs radically from that of the other contactors illustrated, the moving contact being operated directly by the plunger of the electromagnet in a manner similar to that adopted for an electro-pneumatic contactor. This design enables a relatively high contact pressure to be employed, in consequence of which increased current-carrying capacity, for a given width of contact, is obtained.

The interlocks are fixed to the front of the contactor and the moving contacts are operated through linkwork from the plunger of the electromagnet. Provision is made for adjusting the stroke of the moving contacts without affecting the contact pressure.

The contactor is supported by two pairs of mica-insulated steel rods, arranged horizontally behind the contactor, as shown in Fig. 140 *b*.

The operating mechanism of the **Metropolitan-Vickers contactor,** Fig. 140 (*c*, *d*), is similar to that of the B.T.-H. contactor, but the interlocks (which are arranged at the back of the contactor) have a rotary instead of a straight-line, motion.

Reverser. A drum type, electrically operated, throw-over switch is employed for reversing the armature connections of each pair of motors. This switch has two positions, viz. "forward" and "reverse," and is operated by two plunger-type electromagnets, the solenoids of which are energized from the master controller. Each reverser is interlocked electrically (by means of auxiliary switches) with the control circuit of its contactor group, so that the latter cannot operate unless the reverser is set correctly.

Master controllers. Two types have been developed, one for non-automatic control and the other for automatic control.

The **non-automatic controller,** Fig. 141, has separate contact drums for controlling the contactors and reverser. These drums are operated in a manner somewhat similar to the power and reversing drums of a tramcar controller. The driving handle, however, is fitted with a small knob, which must be held depressed during normal operation, otherwise power will be cut off from the control bus-line and an emergency application of the brakes will be made. A handle with such features is called a

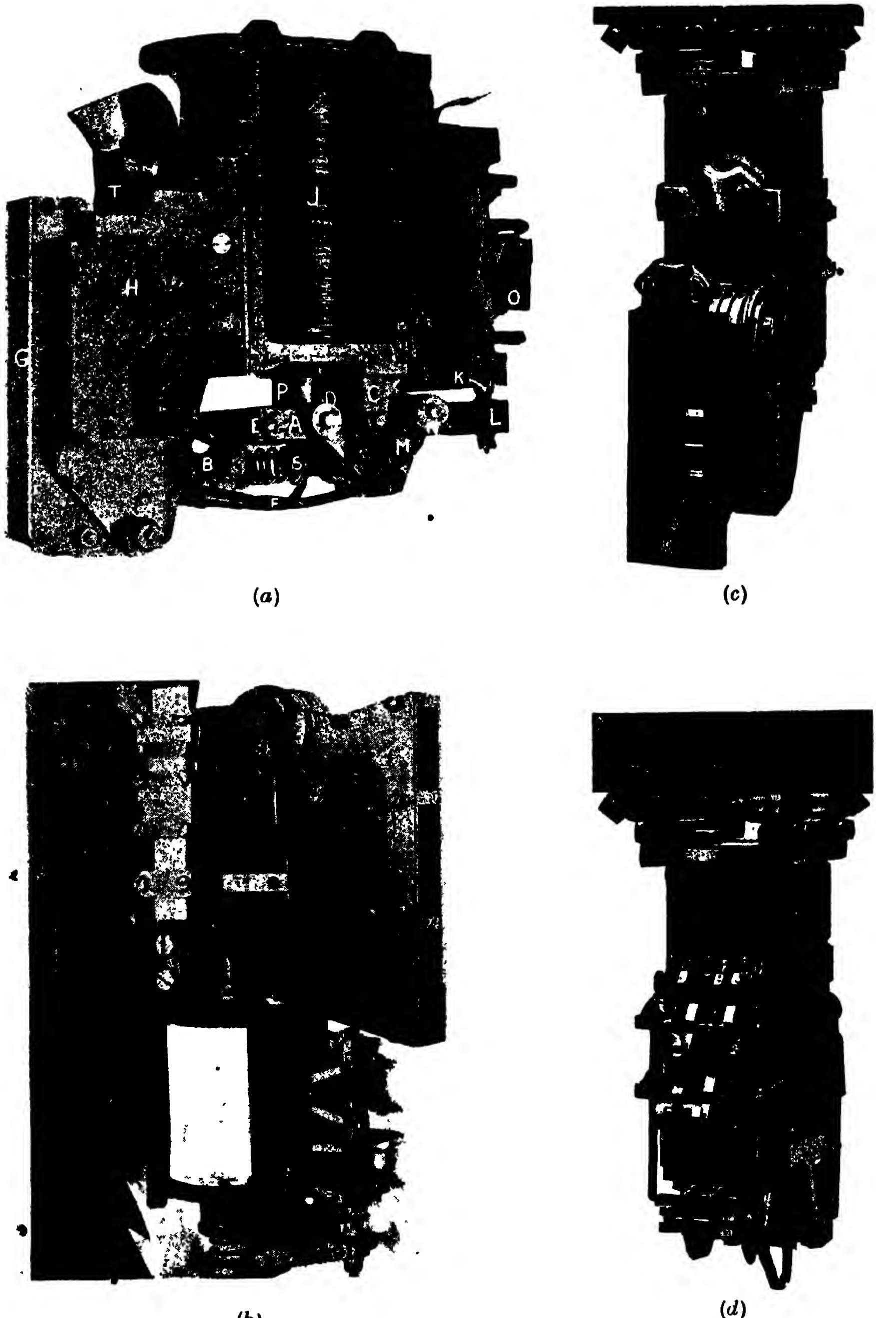


Fig. 140.—Electro-magnetic Contactors. (a) B.T.-H.; (b) G.E.C. (c), (d), Metropolitan-Vickers.

"**dead man's handle,**" as it ensures the stopping of the train in the event of any accident happening to the driver.

The main contact drum, *A*, is fitted with segments to correspond to the several control steps or notches and is operated through gearing, in order that a 180° movement of the driving handle shall give nearly a full revolution of the contact drum. This feature enables a relatively small diameter to be employed for the contact drum, and also permits the controller to be mounted directly against the vestibule of a coach. The fingers, *B*, are connected to the operating coils of the contactors (via the control bus-line) and are provided with a magnetic b'ow-out of the "shaft" type, the blow-out coil being shown at *C*. The arc deflectors *D* are mounted on a hinged pole-piece *E*, which fits against a projection *F*, forming part of the controller base.

A pair of contacts *J*—located in a chamber of fireproof insulation and provided with a blow-out coil *H*—are fixed to the controller-back just above the contact drum, and are connected in series with the fingers supplying the control current to both main and reversing drums. They are bridged by the fingers *G* when the driving handle, *with the knob, M, depressed*, is moved to the operating positions, but should this knob be released when the handle is in any operating position, the fingers, *G*, immediately open the control circuit. At the same time an emergency application of the brakes is made. The contacts *J* can be re-closed only by returning the driving handle to the "off" position and again notching-up with the knob depressed.

The automatic opening of the auxiliary contacts by the release of the knob *M* is effected by the lever *K* in conjunction with the spring *L*. The latter is loose on the shaft *S*, but its upper end may be coupled thereto by depressing the knob, provided that the driving handle is in the "off" position. The lower end of the spring is connected to the lever *K* in such a manner that when torsion is applied to the spring the lever is moved and the fingers *G* close the control circuit at the contacts *J*. The knob *M*, when depressed, also closes a pilot valve (which is spring-biased to the open position) connected to the train pipe of the air brake. This valve is cut out of action when the reversing handle is in the "off," or neutral, position.

The reversing drum, *N*, is a two-way switch and is connected to the solenoids of the reverser.

Two types of **master controllers for automatic control** are shown in Fig. 142. One controller, Fig. 142(*a*), has a single operating handle with a spring-return to the "off" position. This handle is fitted with a knob for controlling a pilot valve in the train pipe, but the valve may be rendered inoperative by inserting a key at *X*. The handle has operating positions on each side of the "off" position.

The other controller, Fig. 142(*b*), has separate operating handles for controlling the contactors and reverser. The segments of the reversing drum are, however, arranged concentric with those of the main drum in order that all fingers may be fixed to a mica-insulated steel bar. The driving handle has the "dead man's handle" feature: its release on any notch automatically returns the upper portion of the main drum to the "off" position and opens a pilot valve connected to the train pipe.

Circuit breaker. An electrically-operated circuit breaker is connected

in the circuit of each group of motors. This circuit breaker follows the general design of the contactors, but is provided with a brush contact, auxiliary (or arcing) contacts, an overload release coil, and a shunt tripping coil. The closing coil is energized from a special switch in the motorman's compartment, and the circuit-breaker is held closed by a

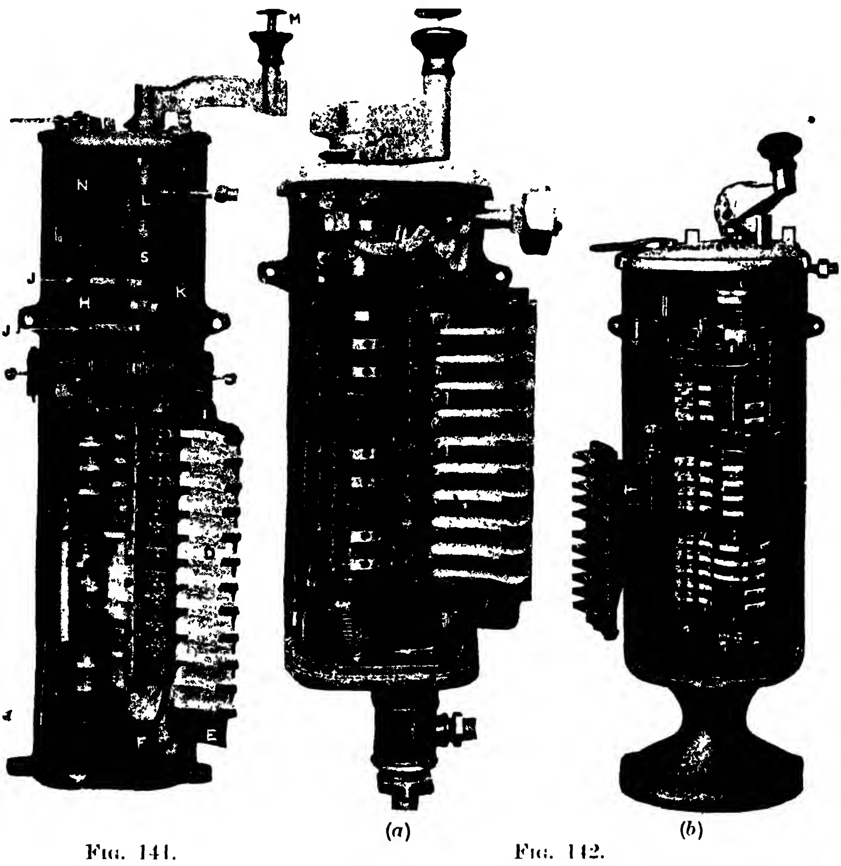


FIG. 141. FIG. 142.

Master Controllers for Multiple-unit Control All-electric Contactor System. Fig. 141 B.T.-H. Controller for Non-automatic Control ; Fig. 142, Controllers for Automatic Control (*a*) B.T.-H., (*b*) M.V.

latch. It is tripped either automatically by the overload coil, or by energizing the shunt-trip coil from a switch in the motorman's compartment.

Typical connections for non-automatic control. A simplified diagram of the motor and control-circuit connections for the bridge method of transition* is given in Fig. 143.† In this diagram the coupler

* The advantages of "bridge" transition have been discussed in Chapter VIII. For multiple-unit operation the method has the further advantage that the principal contactors and rheostats of a two-motor equipment have only to carry the current of one motor.

† This diagram refers to the B.T.-H. non-automatic control equipments in service on the London Underground Electric Railways.

sockets and the auxiliary switches for the control circuit are also shown.

The auxiliary switches or interlocks on the contactors are of two types—one type in which the auxiliary contacts are closed when the contactor is open, and the other type in which the auxiliary contacts are closed when the contactor is closed.

The **operation** is as follows—

On the first notch of the master controller a circuit is established through one of the coils of the reverser and the operating coils of contactors 5, 6, 8, 14. Observe that these contactors can only close provided that Nos. 1 and 13 are open. On the second notch, another circuit is established via the operating coil of contactor 12. On the third notch, the coils of contactors 2 and 11 are connected in series with the coil of No. 12; while, on the fourth and fith notches, the coils of contactors 3, 10 and 4, 9 are added respectively to the series. When No. 9 closes, its auxiliary contacts energize the operating coil of No. 13; and when this contactor closes the operating coil of No. 8 is opened automatically by the auxiliary contacts on No. 13. The main current has now a direct path through contactor 13, and consequently the contactors 2, 3, 4, 9, 10, 11, 12 may be opened without interrupting the motor circuit. This operation takes place on the transition notch. On the first parallel notch a circuit is established from the negative pole of the supply, through the coils of contactors 7 and 1, thence to the positive pole through the operating coils of contactors 5, 6, 14, and the reverser. (The closing of contactor 1 automatically opens contactor 13.) Another path is also formed through the operating coil of contactor 12. The remaining notches operate the contactors 2, 11; 3, 10; and 4, 9.

The interlocks on contactors 6 and 7 are connected in the circuit of the closing coil of the circuit breaker, so that the latter cannot be closed unless these contactors are open. Moreover, the closing coil of the circuit breaker is connected, through the master controller, to a special switch, which is supplied through the master controller switch (see Fig. 143). As the latter switches are "off" except at the driving master controller, the driver has complete control (by means of train wires 5 and 7) over all the circuit breakers on the train; but although these circuit breakers may be tripped at any notch of the controller, they can only be closed when the master controller is in the "off" position.

The cross-connection of the reverser wires (0 and 8) should be noted. This cross-connection is necessary because the "forward" position of, say, the front master controller must correspond to the "reverse" position of the rear master controller.

Automatic control. The essential feature of automatic control is the use of current-limit relays for controlling the operation of the contactors, one current-limit relay being provided for each series-parallel motor-controller.

The **general scheme of operation** is that, as each "resistance contactor" closes, it transfers (by means of auxiliary contacts) its operating coil from an *actuating circuit* (which includes the contacts of the relay) to a *retaining circuit* (which is independent of the relay contacts), and connects the operating coil of the contactor for the succeeding

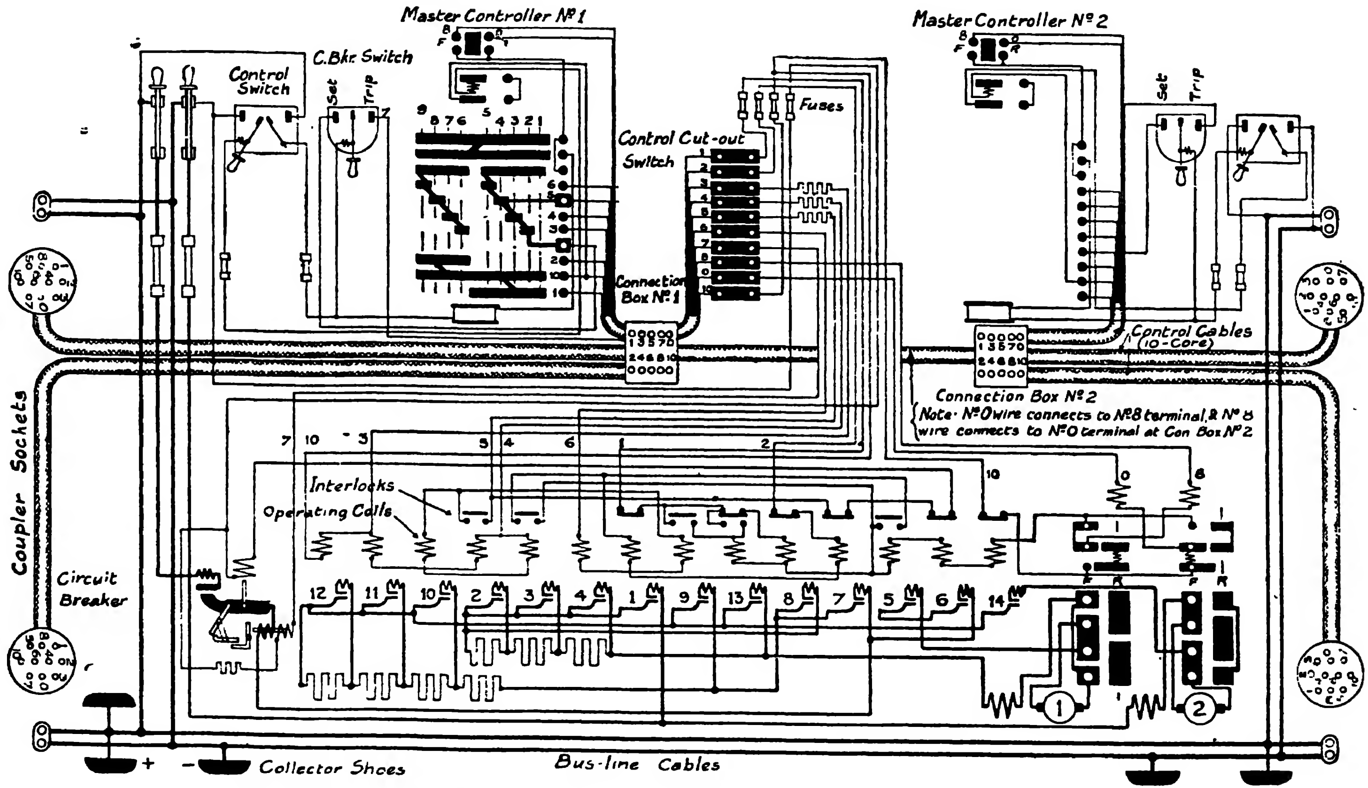


FIG. 143.—Connections for B.T.-H. (Type M) Control System using Bridge Transition.

NOTE.—The interlocks are shown in the "open" position of the contactors. When the contactors close, the short-circuiting bridges of the interlocks move downwards.

step to the actuating circuit via the contacts of the relay. These contacts are closed when the motor current is below a prescribed value, but are open when the current exceeds this value. Hence, if the relay contacts

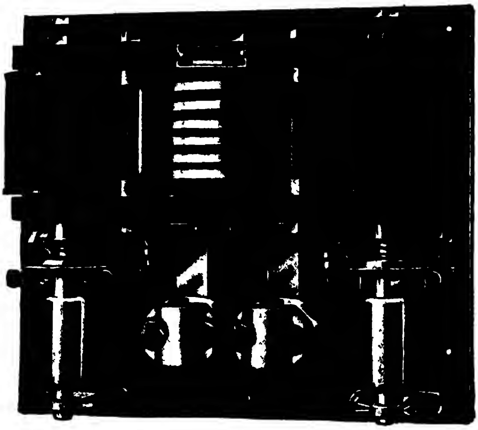


FIG. 144

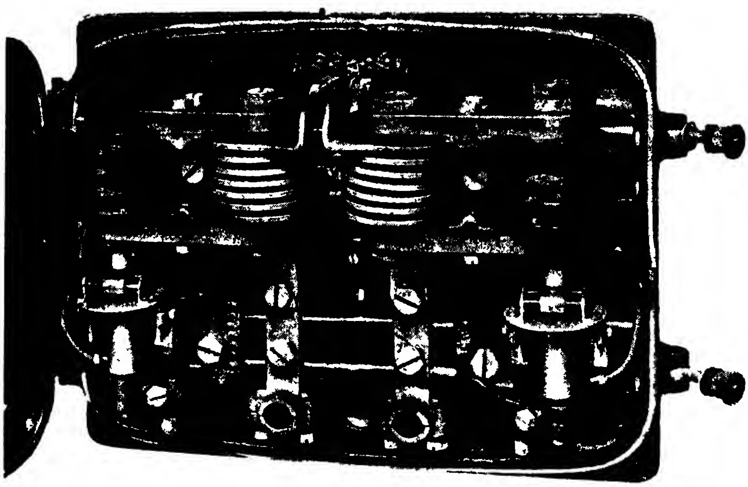


FIG. 145.

B.T.-H. and G.E.C.-Oerlikon Accelerating Relays for Automatic Control.

are closed, the contactor connected to the actuating circuit will be closed; and will, in turn, transfer its operating coil to the retaining circuit. The contactors will automatically "notch-up," step by step, until the motor combination corresponding to the position of the master controller is reached, the rate at which the notching progresses being

controlled indirectly by the motor current. The notching, however, may be arrested at any point, if desired, by a backward movement of the master controller.

Since the resistance steps are cut out only when the motor current falls to the prescribed value, it is possible, by correctly grading the rheostats, to obtain the same variation of motor current on each notch, so that the average accelerating current, and therefore the *average acceleration, will be constant.* It should be noted that this constant average acceleration is obtained not through the skill of the motorman, but through the agency of relays, combined with the correct grading of the rheostats.

A *line, or potential, relay* is also necessary on each motor coach equipped for automatic control. This relay has a shunt-wound operating coil—which is connected, together with a suitable series resistance, across the motor circuit—and contacts which are connected in series with the "retaining" circuit, these contacts being closed when the operating coil is excited.

The object of this relay is to interrupt the control circuit when the voltage is removed from the motor circuit. For instance, if a train of several motor coaches is operated without a "bus-line" cable (i.e. a cable interconnecting the collector shoes, of like polarity, throughout the train), the motor circuits are supplied through the individual collector shoes on each motor-coach, while the whole of the control circuits are supplied from the driving coach. Hence if, say, the rear motor-coach passes over a dead section, the line relay interrupts the control circuit on that coach, and closes it again automatically when the voltage is restored to the collector shoes. The contactors, therefore, must "notch-up" again in the same manner as if they were controlled by the master controller.

A typical current-limit relay is illustrated in Fig. 144. It consists of two potential coils and a current coil, arranged on a common magnetic circuit. Each potential coil is provided with a plunger, which carries a metallic disc capable of short-circuiting a pair of contacts when the plunger is in its lowest position. The plungers are provided with an adjustable time-limit device, the purpose of which is explained later. The potential coils are connected in the circuits of the operating coils of the contactors, and the current coil is connected in the motor circuit.

A modified form of relay is shown in Fig. 145. In this case two current coils (which are connected in series) are employed, together with separate magnetic circuits for the corresponding potential and current coils.

Connections for automatic control. Schematic diagrams of the motor and control circuits are given in Figs. 146, 147,* and a simplified diagram of typical connections is given in Fig. 148.† In both cases the control circuit is supplied directly from the traction circuit (at 600 volts). Hence

* These connections and the scheme of numbering the contactors are typical of the Metropolitan-Vickers control systems on the Southern Railway's motor-coach trains.

A more elementary and introductory treatment of automatic control, together with simple circuit diagrams, is given in the Author's *Traction Motor Control* (Pitman's Technical Primer Series, 2s. 6d. net).

† These connections and the scheme of numbering the contactors are typical of the British Thomson-Houston Co.'s control system installed on some of the trains operating on the Central London and the London Underground Railways.

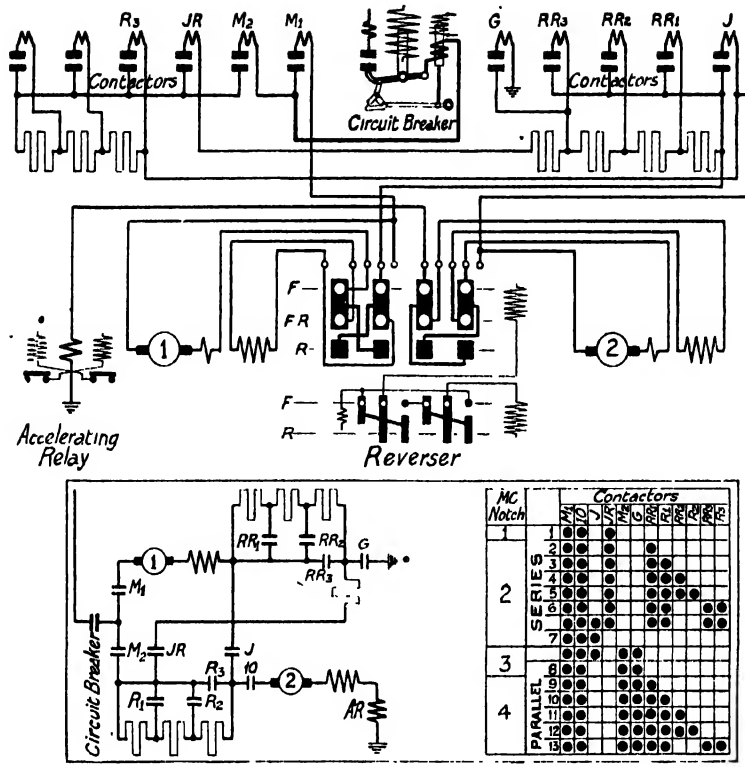


FIG. 146.—Main-circuit Connections for Metropolitan-Vickers Automatic All-electric Control System.

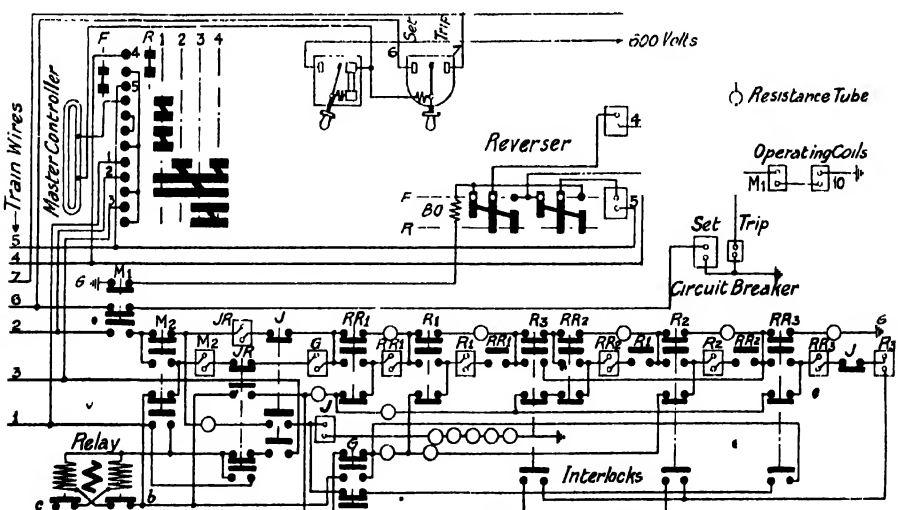


FIG. 147.—Control-circuit Connections for Metropolitan-Vickers Automatic All-electric Control System.

as the contactor operating coils are designed for 100 volts, the operating circuits must always include six coils or their equivalent in resistance.

The control-circuit bus-line cable consists of seven wires, of which five are for the purpose of controlling the contactors and the remaining two are for the purpose of controlling the automatic circuit-breaker. Each of the wires constituting the control circuit proper has a definite function: thus No. 1 wire controls the "actuating" circuit of the contactors; No. 2 wire controls the "retaining" circuit of the contactors; No. 3 wire controls the transition into parallel; and wires Nos. 4 and 5 (or 8 and 0, Fig. 148) control respectively the "forward" and "reverse" operating coils of the reverser, as well as the "line" contactor and the contactor in No. 2 motor circuit.

When the master controller is placed on the first (series) notch "forward," two circuits are established. One circuit is from No. 5 finger (Fig. 147), through the "forward" operating coil and interlocks of the reverser,* through the operating coils of contactors M_1 and 10, and thence to earth through a rheostat. The other circuit is from No. 2 finger, through the interlocks of contactors M_1, M_2, and thence through the operating coil of the "series" contactor (JR) to earth via the auxiliary contacts of contactors M_1, M_2, J, RR_1, R_1, R_3, RR_2, R_2, RR_3, and a number of substitutional resistances. This circuit forms the "retaining" circuit for the contactors which are subsequently energized automatically. In practice the contacts of the line relay are included in this circuit, and therefore the series contactor cannot be energized unless the circuit breaker and main switch are closed and sufficient voltage is available at the collector shoes (see Fig. 148).

If the master controller is moved to the second notch, another circuit (called the "actuating" circuit) is established by means of wire No. 1 and the current-limit or accelerating relay. This circuit, however, is under the control of the relay, and the contactors will be energized only provided that the relay contacts are short-circuited. As neither potential coil of the relay is energized on the first notch of the controller, the relay contacts will be short-circuited when the controller moves to the second notch, and, therefore, a circuit will be established through the operating coil of contactor RR_1 to earth, via the contacts (b) of the relay and the interlocks of contactors RR_1, JR, R_1, R_3, RR_2, R_2, RR_3. When contactor RR_1 closes, its operating coil is transferred automatically to the "retaining" circuit (energized from No. 2 wire) by means of the interlocks on this contactor, and, at the same time, the circuit of the potential coil (c) of the relay is opened. Before this change has taken place, however, the plunger controlling contacts (c) of the relay—from which the succeeding contactor, R_1, is energized—will have been lifted, and the time-limit device on the plunger will prevent the premature release of the latter when the circuit of the potential coil is opened. Therefore, the contacts (c) cannot close until the plunger is released by the series coil, which occurs when the motor current falls to the predetermined value at which the relay is set. Contactor R_1 will then be energized, via the contacts (c) of the relay and the interlocks of contactors G, R_1, RR_1, R_3, RR_2, R_2, RR_3.

* If the reverser is in the "reverse" position, the "forward" coil is energized with the full line voltage provided that contactor M_1 is open.

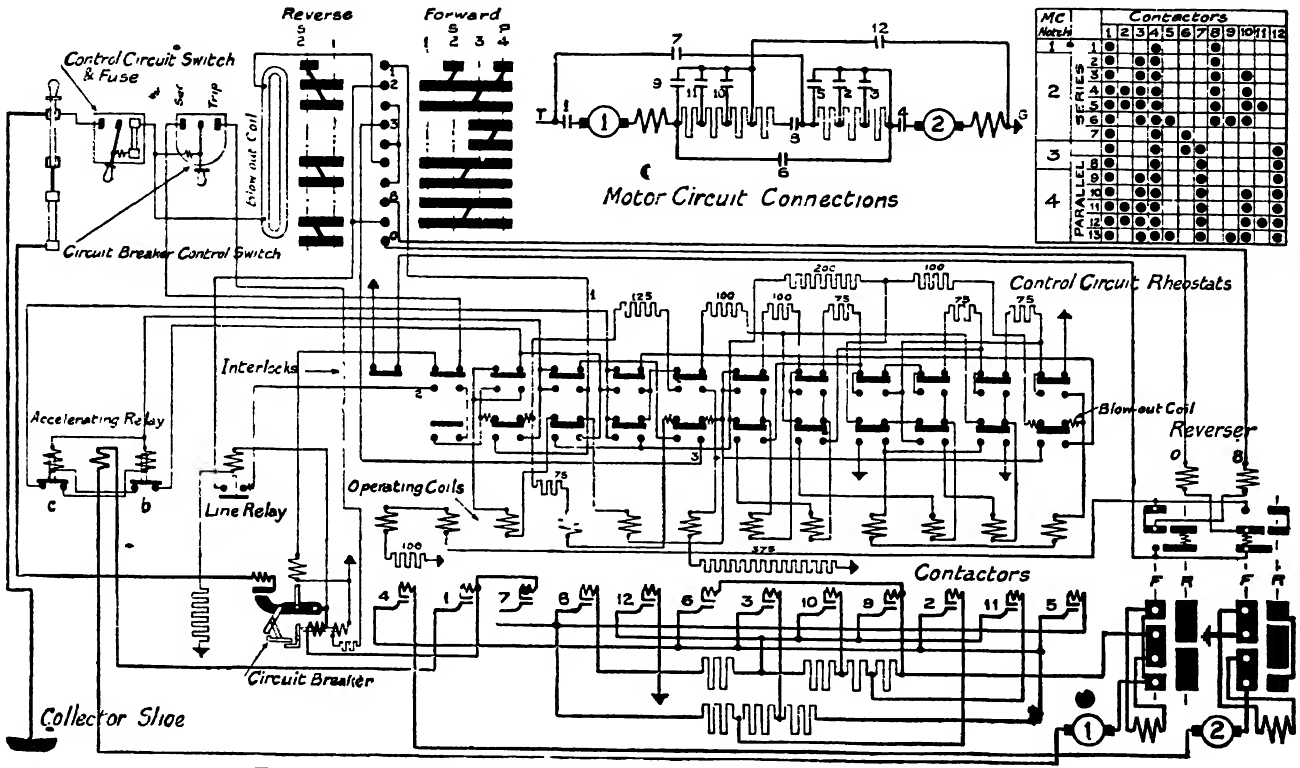


FIG. 148.—Connections for Sprague B.T.-H. Automatic Control System.

NOTE.—The interlocks are shown in the "open" position of the contactors. When contactors close, the short-circuiting bridges of interlocks move downwards. The numbers against the control-circuit rheostats refer to their resistances (ohms). The coupler sockets, connection boxes, and cut-out switches are not shown.

TABLE SHOWING PATHS OF CONTROL CIRCUITS FOR FIG. 148.

Master Controller Notch.	Step.	"Actuating" Circuit.	"Retaining" Circuit.	"Reverser" Circuit.
1	1		$\mathrm{II}-LR-1i_2-1i_4-7i_3-75-8c-6i_3-3i_1-100-10i_1-75-9i_1-2i_1-75-11i_1-75-5i_1-G.$	$\mathrm{VIII}-Rc-Ri-1c-4c-100-G.$
2	2	$\mathrm{I}-8i_2-AR_b-8i_4-3i_3-3c-10i_1-75-9i_1-2i_1-75-11i_1-75-5i_1-G.$	$\mathrm{II}-LR-1i_2-1i_4-7i_3-75-8c-6i_3-3i_2-3c-10i_1-75-9i_1-2i_1-75-11i_1-75-5i_1-G.$	" "
2	3	$\mathrm{I}-8i_2-AR_c-12i_3-6i_1-100-10i_3-10c-3i_4-9i_1-2i_1-75-11i_1-75-5i_1-G.$	$\mathrm{II}-LR-1i_2-1i_4-7i_3-75-8c-6i_3-3i_2-3c-10i_2-10c-3i_4-9i_1-2i_1-75-11i_1-75-5i_1-G.$	" "
2	4	$\mathrm{I}-8i_2-AR_b-8i_4-200-9i_3-2i_3-2c-10i_4-11i_1-75-5i_1-G.$	$\mathrm{II}-LR-1i_2-1i_4-7i_3-75-8c-6i_3-3i_2-3c-10i_2-10c-3i_4-9i_1-2i_2-2c-10i_4-11i_1-75-5i_1-G.$	" "
2	5	$\mathrm{I}-8i_2-AR_c-12i_3-6i_1-100-11i_3-11c-2i_4-5i_1-G.$	$\mathrm{II}-LR-1i_2-1i_4-7i_3-75-8c-6i_3-3i_2-3c-10i_2-10c-3i_4-9i_1-2i_2-2c-10i_4-11i_2-11c-2i_4-5i_1-G.$	" "
2	6	$\mathrm{I}-8i_2-AR_b-8i_4-200-100-5i_3-5c-9c-11i_4-G.$	$\mathrm{II}-LR-1i_2-1i_4-7i_3-75-8c-6i_3-3i_2-3c-10i_2-10c-3i_4-9i_2-5i_2-5c-9c-9i_4-G.$	" "
2	7	$\mathrm{I}-8i_2-AR_c-12i_1-5i_4-6c-375-G.$	$\mathrm{II}-LR-1i_2-1i_4-7i_3-125-6i_2-6c-375-G.$	" "
3	Tr. & 8	$\mathrm{III}-6i_4-8i_1-AR_b-7i_1-7c-8i_3-12c-3i_1-100-10i_1-75-9i_1-2i_1-75-11i_1-75-5i_1-G.$	$\mathrm{II}-LR-1i_2-1i_4-7i_2-7c-8i_3-12c-3i_1-100-10i_1-75-9i_1-2i_1-75-11i_1-75-5i_1-G.$	" "
4	9	$\mathrm{I}-7i_4-AR_c-12i_4-3i_3-3c-10i_1-75-9i_1-2i_1-75-11i_1-75-5i_1-G.$	$\mathrm{II}-LR-1i_2-1i_4-7i_2-7c-8i_3-12c-3i_3-3c-10i_1-75-9i_1-2i_1-75-11i_1-75-5i_1-G.$	" "
4	10	$\mathrm{I}-7i_4-AR_b-12i_2-6i_1-100-10i_3-10c-3i_4-9i_1-2i_1-75-11i_1-75-5i_1-G.$	$\mathrm{II}-LR-1i_2-1i_4-7i_2-7c-8i_3-12c-3i_2-3c-10i_2-10c-3i_4-9i_1-2i_1-75-11i_1-75-5i_1-G$	" "
4	11	$\mathrm{I}-7i_4-AR_c-12i_4-200-9i_3-2i_3-2c-10i_4-11i_1-75-5i_1-G.$	$\mathrm{II}-LR-1i_2-1i_4-7i_2-7c-8i_3-12c-3i_2-3c-10i_2-10c-3i_4-9i_1-2i_2-2c-10i_4-11i_1-75-5i_1-G.$	" "
4	12	$\mathrm{I}-7i_4-AR_b-12i_2-6i_1-100-11i_3-11c-2i_4-5i_1-G.$	$\mathrm{II}-LR-1i_2-1i_4-7i_2-7c-8i_3-12c-3i_2-3c-10i_2-10c-3i_4-9i_1-2i_2-2c-10i_4-11i_2-11c-2i_4-5i_1-G.$	" "
4	13	$\mathrm{I}-7i_4-AR_c-12i_4-200-100-5i_3-5c-9c-11i_4-G.$	$\mathrm{II}-LR-1i_2-1i_4-7i_2-7c-8i_3-12c-3i_2-3c-10i_2-10c-3i_4-9i_2-5i_2-5c-9c-9i_4-G.$	" "

NOTE.—Roman numerals I, II, III, VIII denote fingers on master controller; Arabic numerals 1–12 denote contactors. 75–375 denote resistances (ohms) of control-circuit rheostats; AR_b, AR_c denote contacts of accelerating relay; LR denotes contacts of line relay; R denotes reverser; c denotes operating coil; i denotes contacts of interlocks (position of interlocks is denoted by suffixes 1–4, the top row of contacts being designated No. 1). For example, the "actuating" circuit for step 2 would be read:—Finger 1—No. 2 interlocks, contactor 8—contacts b, accelerating relay—No. 4 interlocks, contactor 8—No. 3 interlocks, contactor 3—coil, contactor 3—No. 1 interlocks, contactor 10—75 ohms—No. 1 interlocks, contactor 9—...... No. 1 interlocks, contactor 5—earth.

Next, contactor RR_2 is energized via the contacts (b) of the relay and contactors JR, R_3, RR_2, R_1, R_2. RR_3.

In a similar manner contactor R_2, and contactors RR_3 and R_3, are energized respectively on the next two notches. The transference of the earth connection of the "retaining" circuit from contactor RR_3 to contactor R_3 should be noted, as well as the automatic opening of contacto s RR_2 and R_2.

On the next notch—the last series notch—the "bridge" contactor J is energized, and when this contactor closes, its auxiliary contacts open the circuit of contactors JR, RR_1, R_1, RR_3, R_3. The contactors closed on the last series notch are, therefore, M_1, 10, J.

It should be noted that no more "notching-up" can take place unless No. 3 wire is energized. Moreover, during the above process of notching-up, the notching can be stopped at any desired point by placing the master controller on the first notch, which interrupts the "actuating" circuit.

If the master controller is moved to the last (or fourth) notch "forward," contactors M_2 and G will be energized from No. 3 wire via the contacts (b) of the relay and contactors J, JR, M_2, JR, RR_1, R_1, R_3, RR_2, R_2, RR_3. When contactors M_2 and G close, the control circuit is transferred to No. 2 wire via the interlocks of contactors M_1, M_2, JR, RR_1, R_1, R_3, RR_2, R_2, RR_3. Thus the object of No. 3 wire is to energize the "parallel" contactors (M_2 and G), and these contactors cannot close until J has closed and JR has opened. At starting, the master controller may be placed directly on the last notch, and "notching-up" will take place through all the series notches, the transition notch, and the parallel notches.

When M_2 closes, J is opened automatically, and the potential coils of the relay are supplied through the auxiliary contacts of M_2. On the series notches the potential coils of the relay are supplied through the auxiliary contacts of JR. Thus the automatic relay can only control the "actuating" circuit, provided that *either* JR or M_2 is closed.

The notching-up to "full parallel" takes place in a manner similar to that for the series steps. Observe, however, that the operation of the contactors is now governed by the current in motor No. 1. On some of the parallel notches the closing of corresponding "resistance" contactors takes place successively instead of simultaneously as with non-automatic control. For example, a rheostat section in No. 1 motor circuit is not cut out until the contactor of the corresponding section in No. 2 motor circuit is fully closed. The next rheostat section in No. 2 motor circuit, however, cannot be cut out until the relay contacts close again.

The provision of duplicate potential coils and contacts on the relay ensures that the control connections are made in the correct order.

The important contactors (e.g. M_1, M_2, G, JR, J) are interlocked in a manner similar to that described above in connection with Fig. 143, while the closing coil of the circuit-breaker is interlocked with M_1, and can only be energized when this contactor is open.

The switching operations for the connection diagram of Fig. 148 are identical with those described above, and can be followed without difficulty from the table on page 217.

Electro-Pneumatic Multiple-Unit Systems

The Metropolitan-Vickers* unit-switch system.—The special feature of this system is that the contactors are operated pneumatically, and the supply of air to the pneumatic cylinders is controlled by electro-magnetic valves which are energized from a low-voltage circuit by a suitable master controller. The electro-pneumatic feature has been developed extensively by the Westinghouse Companies for all classes of railway control apparatus, and further examples of the application of this system will be found in Chapters X, XI.

The **control equipment** includes a group of electro-pneumatic contactors (called a "switch group"), an electro-pneumatic reverser, a master controller, a source of low-voltage supply for control circuit (which may consist of duplicate 14-volt storage batteries, a motor-generator set, or a tapped resistance connected across the traction circuit), the necessary control-circuit cables and switchgear, and, usually, relays for automatic acceleration.

A view of a **contactor** or "unit switch" is shown in Fig. 149. The cylinder *A* is single-acting, and the piston *B* is biased towards the lower position by a spring. The moving contact, *C*, is fitted to an insulated extension of the piston-rod, and an arm, *D*, carries the segments of the auxiliary contacts. The admission valve *V* is maintained on its seat by a spring, and is opened by the plunger of the solenoid *S*. This plunger also controls the exhaust valve, which is similar to that of the "on" magnet, Fig. 155. A push-button located above the upper end of the plunger, enables the valves and contactor to be tested without supplying power to the solenoid. When the solenoid is energized, the cylinder is supplied with compressed air at a pressure of about 70 lb. per sq. in., and the main contacts are closed with considerable pressure. These contacts are located in an arc chute, of fireproof material, and are provided with a blow-out coil.

The parts of the contactor are clamped to bakelized steel bars, so that each contactor forms an individual unit.

The requisite number of contactors for the control of a pair of motors are assembled in a common frame to form a "**switch group,**" a typical example being shown in Fig. 150. This switch group is representative of Metropolitan-Vickers, 1500-volt, motor-coach automatic equipments for heavy suburban service. The contactors, reverser, relays for automatic acceleration and overload protection, and motor cut-out switches are arranged in two cast-iron frames for convenience in mounting on the underframe of the coach.

The **reverser,** Fig. 151, is of the drum type and is operated by a rack and pinion, the rack forming the common piston rod for two opposed pistons working in a pneumatic cylinder similar to that shown in Fig. 155.

The accelerating relay (for automatic control) is much simpler than that for the electromagnetic contactor system, as, with electro-pneumatic operation, a single-plunger relay with a single (series) operating is satisfactory. A typical relay is illustrated in Fig. 152 (*a*). The small shunt coil, located above the series coil, is excited only in the parallel combination of the motors, and is for the purpose of obtaining a lower limit of

* Formerly the British Westinghouse Co.

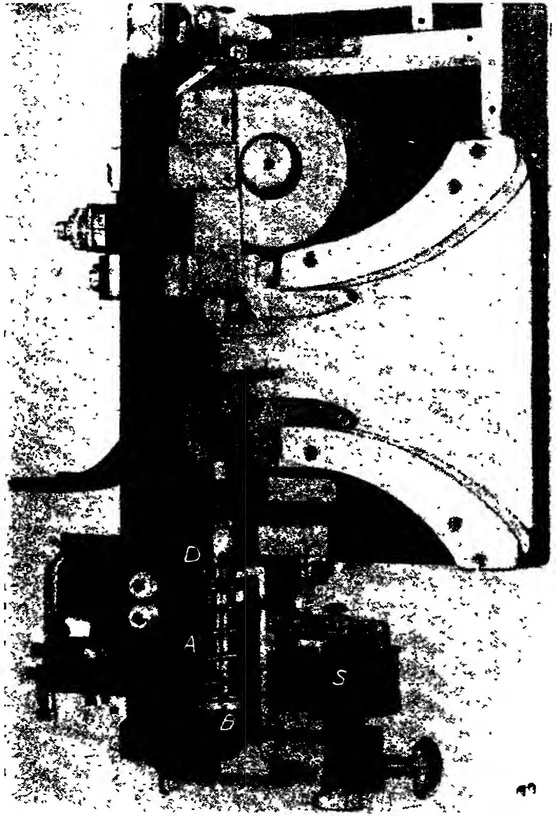


Fig. 149.—Metropolitan-Vickers Electro-pneumatic Contactor, Sectioned to show Construction.

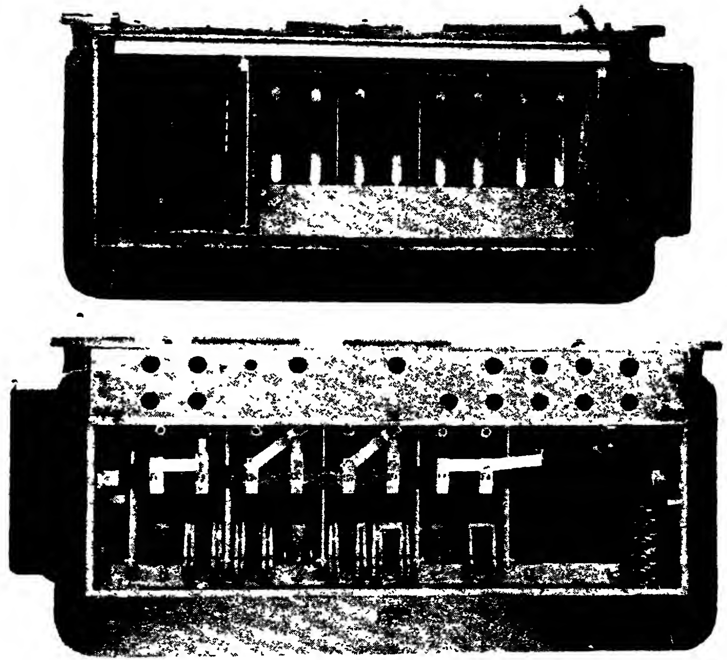


Fig. 150.—Metropolitan-Vickers Electro-pneumatic Switch Group. (Front and Back Views, showing Contactors and Reverser.)

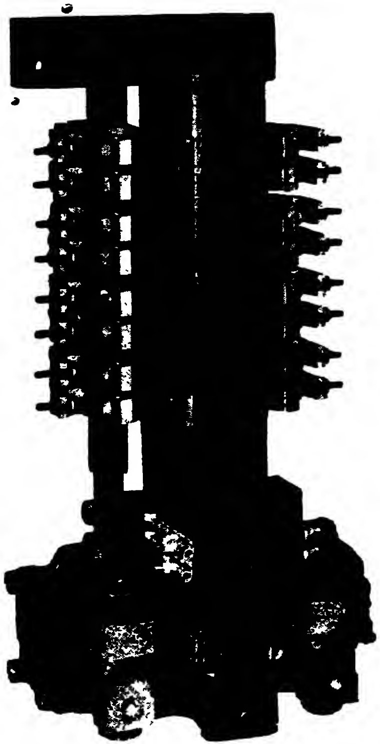
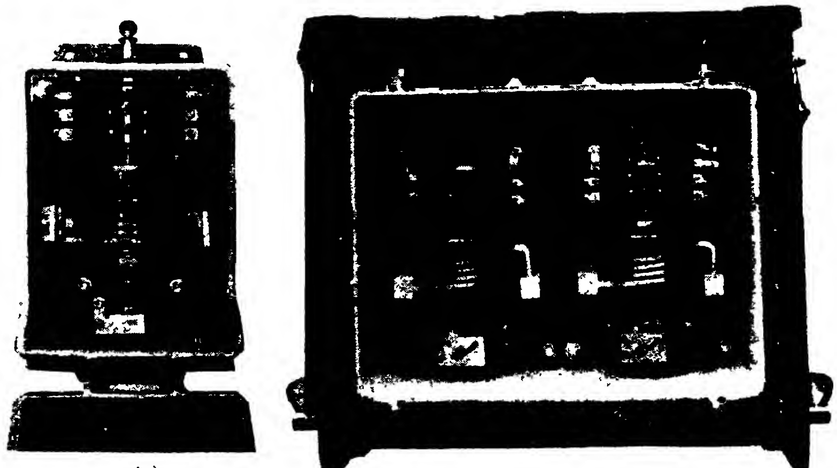


Fig. 151.—Electro-pneumatic Reverser.



(a) (b)

Fig. 152.—Accelerating (a) and Overload (b) Relays for Metropolitan-Vickers Electro-pneumatic Control System.

accelerating current for this combination than for the series combination. The peak load on the substations and distributing system is, therefore, lower than it would be if the full accelerating current were maintained throughout the whole of the starting period.

The overload relays are shown in Fig. 152(*b*). Two relays are employed —one being connected in series with each motor—in order to obtain full protection in both combinations of the motors. The relays are not self re-setting, and, after tripping, the plungers are held up by latches, which can only be released by energizing special re-setting coils.

Connections for automatic control. Schematic diagrams of the main-circuit and control-circuit connections for the switch group shown in

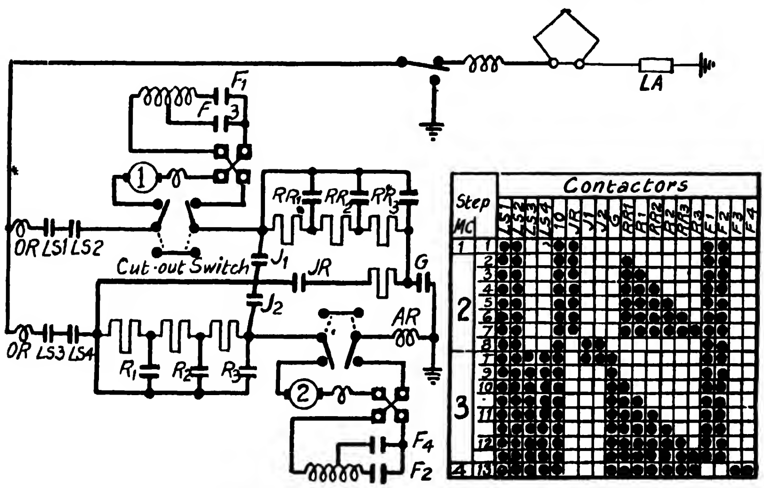


FIG. 153. Main-circuit Connections for Metropolitan-Vickers Electro-pneumatic 1500-volt Control System.

Fig. 150 are given in Figs. 153, 154. The transition is by the bridge method, and the motor field windings are tapped in the parallel combination of the motors.

The control circuit is supplied at low voltage from a motor-generator set, and in consequence of the low voltage and the small power required by the valve-magnet solenoids, no blow-out coils are necessary for either the master controller or the interlocks on the contactors. Moreover, owing to the valve-magnet coils being arranged for parallel connection, the control-circuit connections are considerably simpler than those for the electromagnetic contactor system, Fig. 147, as the correct automatic sequence of the "resistance" contactors can be obtained with very simple auxiliary switches.*

The **master controller** has separate handles for the "power" and "reversing" drums, the former having four operating positions, viz.

* Elementary diagrams showing a direct comparison between the control-circuit wiring and switching for automatic control with electromagnetic and electro-pneumatic contactors are given on pp. 98–104 of the Author's *Traction Motor Control* (Pitman's Technical Primer Series, 2s. 6d. net).

(1) first series, (2) full series, (3) full parallel, (4) weak fields. The " dead man's " feature is incorporated.

The control-circuit supply to the master controller is taken through the contacts of a pneumatic switch (called a " control governor "), in

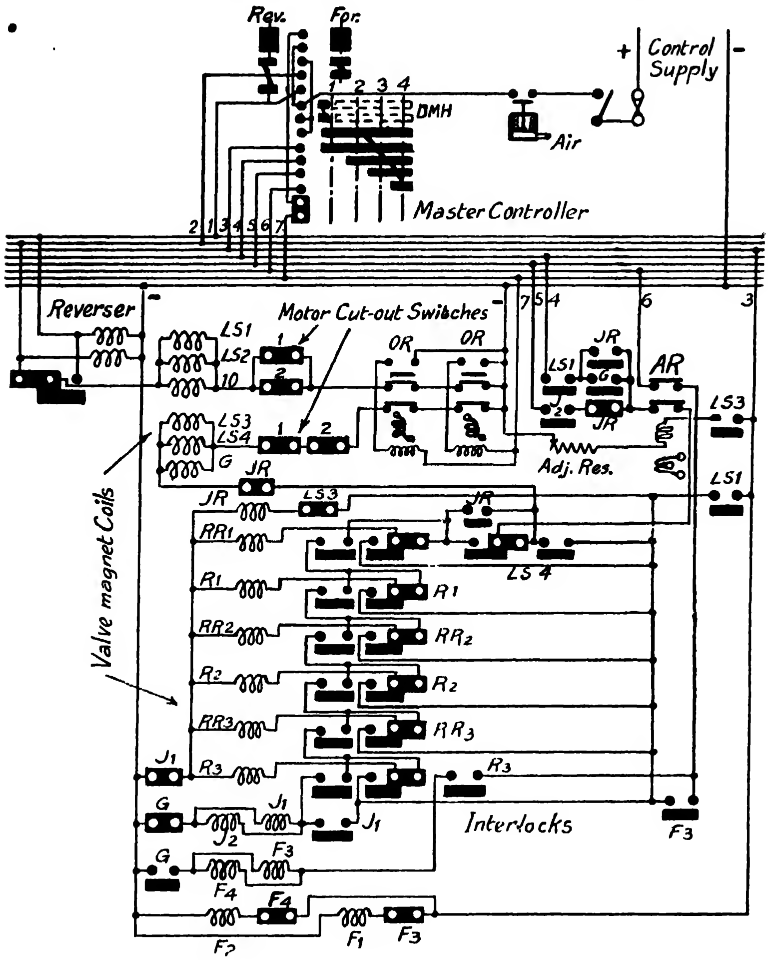


Fig. 154.—Control-circuit Connections for Metropolitan-Vickers Electro-pneumatic Control System.

The interlocks are shown in the " open " position of the contactors.
Note.—*AR*, *OR*, denote the accelerating relay and the overload relays, respectively.

addition to the usual isolating switch. The control circuit is therefore interlocked with the air supply, and the circuit to the master controller is closed only when the air pressure is above a definite value.

The sequence of operations is briefly as follows—

When the reversing handle is thrown to an operating position the re-set coils of the overload relays are energized via wire 7.

When the driving handle is moved to the first position, the circuit to the re-set coils is broken, and a circuit is established to wires 1 or 2 (according to the position of the reversing drum) and also to wire 3, in the circuit of which is included the contacts of the "dead man's" feature. (These contacts are also included in the circuits of wires 4, 5, 6, which are energized on subsequent steps.) The reverser is therefore set, and its interlocking contacts energize (via wires 1 or 2) the magnets of contactors LS_1, LS_2, 10. Observe that this circuit includes the contacts of the overload relays and the auxiliary contacts on the motor cut-out switches.

Wire 3 establishes the circuits to the "full-field" contactors, F_1, F_2, and the "series" contactor JR; the former being interlocked with the field-tapping contactors F_3, F_4, and the latter being interlocked with the line contactors LS_1, LS_3. Thus contactors LS_1, LS_2, 10, F_1, F_2, JR are closed, and the motors are connected in series with each other and with the full resistance in the circuit.

When the driving handle is moved to the second position the "actuating" circuit is established, and contactor RR_1 closes, provided that the motor current has fallen to the prescribed value. Observe that the circuit to the accelerating relay includes the interlocking contacts on contactors LS_1, JR. The closing of contactor RR_1 transfers its magnet coil to the "retaining" circuit—which is supplied by wire 3—and connects the magnet coil of contactor R_1 to the "actuating" circuit. Automatic action then continues until the "bridge" contactors J_1, J_2 (two contactors being connected in series) close and the "full series" step is obtained. Observe that when J_1 closes, its interlock opens the circuit of the magnet coils of contactors JR, RR_1, R_1, RR_2, R_2, RR_3, R_3. Observe also that the opening of JR opens the "actuating" circuit.

The "transition-actuating" circuit is established, via wire 5, at the third position of the master controller, and, if the motor current is below the prescribed value, the "parallel" contactors—LS_3, LS_4, G- are closed and the bridge contactors are opened. Observe that the closing of LS_4 transfers the magnet coils, LS_3, LS_4, G, to the "retaining" circuit supplied by wire 3, and that the closing of G opens the circuit of J_1, J_2. Observe also the interlocking of the "parallel" contactors with both the "series" contactor and the auxiliary contacts of the motor cut-out switches, the re-establishment of the "actuating" circuit (via wire 4), and the energizing of the auxiliary shunt coil of the accelerating relay.

On the last step of the controller the control circuit of the field-tapping contactors, F_3, F_4, is established via wire 6, the special contacts of the accelerating relay, and the interlocks on contactors R_3 and G. Hence tapped-field operation cannot be obtained until the motors are in "full" parallel and the current is below the prescribed value.

Electro-pneumatic drum controllers. Although the electro-pneumatic operation of a series-parallel drum-type controller was developed (for multiple unit working) by the Westinghouse Co. a number of years ago,* and abandoned in favour of electro-pneumatic contactors, the principle has recently been re-introduced for small equipments. The multiple-unit

* This system of control is in service on the Mersey Railway. For a description of the controllers and method of operation see *The Electrical Review*, vol. 49, p. 975; *The Electrician*, vol. 51, p. 5.

operation of a number of small cars can, therefore, be obtained by the addition of an operating head to the existing controllers, and the provision of master controllers and the necessary control-circuit cable. Automatic control and other features common to multiple-unit equipments can be obtained by the further addition of an electro-pneumatic contactor (or circuit breaker) and an accelerating (or current-limiting) relay.

In these equipments—which have been supplied to the New York street railways—the standard platform controller is fitted with a pneumatic operating head, and the controller is operated electro-pneumatically from a master controller. Only one main controller is therefore necessary on a car, and, since this controller is remote controlled, it may be located in any convenient part of the car.

The main contact drum is operated by a rack and pinion, as shown in Fig. 155. The rack forms the common piston-rod for two pistons,

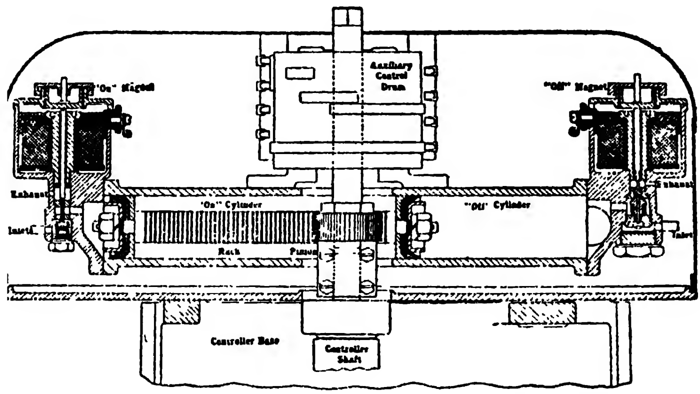


FIG. 155. Section of Cylinder and Valves of Westinghouse Electro-pneumatic Operating Head for Drum Controller.

which operate in a double-acting pneumatic cylinder. The air supply to this cylinder is controlled by electromagnetic valves, which are energized from the master controller. The " on " magnet admits compressed air to the " on " cylinder, and the " off " magnet, when energized, releases the air from the " off " cylinder. The forward movement of the controller drum is obtained by energizing both magnets simultaneously, which results in the admission of air to the " on " cylinder and the release of air from the " off " cylinder. The return movement of this drum is obtained by cutting off the current from the valve magnets, which results in the admission of air to the " off " cylinder and the release of the air in the " on " cylinder. To stop the forward movement the air pressure in the " on " and " off " cylinders is equalized by breaking the circuit of the " off " valve magnet. Thus the whole of the movements of the controller-drum are governed by the *difference* of air pressure in the two cylinders, and, on account of this feature, the operating device is sometimes referred to as a " differential air engine."

In order to obtain the correct notches on the controller, the control circuit of the " off " magnet is broken on an auxiliary interlocking drum,

which is connected to an extension of the controller shaft. The positions of the segments on this drum correspond to the notches on the main drum, and the fingers corresponding to these segments are supplied from the master controller through separate wires.

The reversing drum of the controller is operated by a separate double-acting cylinder.

Recent developments include: (1) Special features in the master controller and interlock drum, to permit of non-automatic control on certain notches and either semi-automatic or full-automatic control on the other notches; (2) means for increasing the setting of the accelerating relay to a predetermined value, thus enabling the mean accelerating current to be increased above the normal value in cases of emergency; (3) an electro-pneumatic "line" contactor, or circuit breaker, for breaking

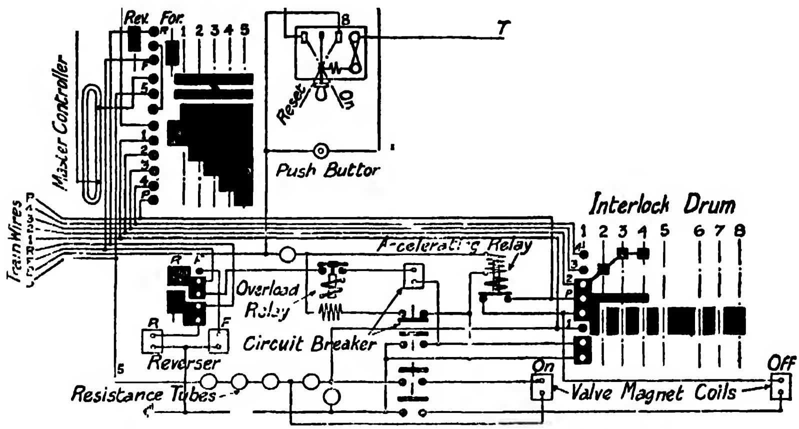


FIG. 156.- Control-circuit Connections for Westinghouse Electro-pneumatic Operating Head.

the motor circuits; (4) an overload relay which is reset electrically; (5) the use of the line supply, instead of a battery, for energizing the valve magnets.

With these developments the system possesses the important advantage that cars having two-motor and four-motor equipments with controllers having different numbers of notches, may be coupled together and operated as a train—provided that the motor characteristics, gear ratios, and wheel diameters are suitable—since the automatic operation of the controller on a particular car is governed by the accelerating relay on that car.

A schematic diagram of the control-circuit connections is given in Fig. 156. The low-voltage supply for the control circuit is obtained from a tapped resistance connected across the 600 volt traction circuit.

The main controller has eight notches, viz., five series and three parallel.

The master controller has five notches, and the main-circuit operations corresponding to these notches are—

On the first notch the reverser is set and the circuit breaker is closed. As the main controller normally stands at its first notch, the closing of

the circuit breaker completes the main circuit. On the second notch the main controller is moved to its second notch, this movement being independent of the relay.

On the third notch the main controller is moved to its third notch under the control of the relay.

On the fourth and fifth notches the main controller is moved automatically to the full-series and full-parallel positions respectively.

The accelerating relay is provided with a differential shunt coil, which, when energized by means of a push-button switch at the master controller, causes the plunger to be released at a higher motor current than that for which the relay is normally adjusted. Hence, when the service conditions are such that the normal accelerating current is insufficient for acceleration (e.g. when starting a car on steep gradient), and the relay is held open—thus preventing the notching-up of the main controller—the setting of the relay is changed (by energizing the shunt coil) and the controller notches-up at a higher accelerating current.

Combination of pneumatically-operated drum controller and contactors. The above method of pneumatically operating a drum controller was developed, primarily, to enable platform-type controllers of existing equipments to be remote controlled, and the cars operated on the multiple-unit system. For new equipments, however, the Westinghouse Co. have developed a control system in which a pneumatically-operated drum controller is combined with a number of contactors. The apparatus is designed as a compact unit for installation under the car floor, and is especially suitable for low-floor cars.

Views of a complete unit are given in Fig. 157, and a diagram of the main-circuit **connections** is given in Fig. 158.

The main circuits are opened and closed by the contactors, while resistance is cut into and out of the motor circuit, and, if necessary, the field-tap connections made by the drum controller. Transition is effected by shunting a pair of motors (Nos. 2 and 4); the first steps of the transition (viz., the cutting-in of a portion of the rheostats and the earthing of the remote ends of the fields of motors Nos. 1 and 3) being performed by the controller, while the completion of the transition is effected by the contactors, the first parallel notch being obtained by opening *S* and closing *P*. During the transition period certain fingers of the controller are subject to arcing, and these fingers are fitted with individual blow-out coils.

Larger equipments, in which bridge transition is adopted, have been developed for motor-coach trains, and are used on an extensive scale by the New York Municipal and Interborough Rapid Transit Railways. The equipments* on these railways are arranged for automatic acceleration and field control.

CAM-SHAFT CONTROL SYSTEMS

Hand-operated cam-shaft controllers—in which the whole of the switching operations (except reversing) are effected by cam-operated

* The motors are rated at 160 h.p., 600 volts. For further details of the cars and equipment see *Electric Railway Journal*, vols. 43, p. 1327; 44, p. 1376; 45, p. 496. For details of the controller see *Electric Motors and Control Systems*, pp. 239–242.

contactors—are in service in this country on some of the larger tramway systems, but on the Continent they are also employed for single motor-coaches and locomotives when multiple-unit working is not required. For 1500- and 3000-volt circuits the controllers are operated through gearing from a dummy controller in the driving position.

For **multiple-unit working** power operation and remote control are necessary. Such (cam-shaft) systems possess important advantages over

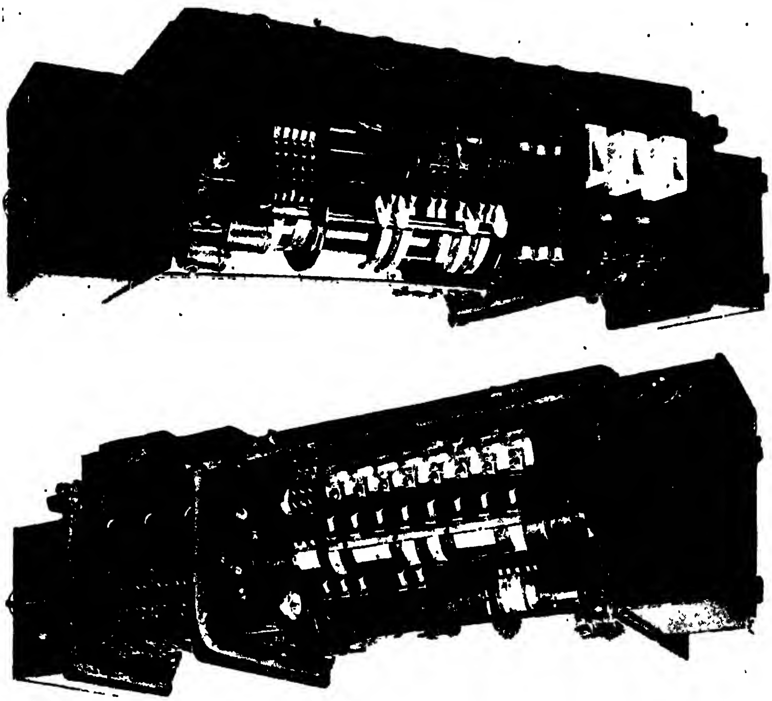


FIG. 157.—Westinghouse Underframe Control Unit for Low-floor Car.

NOTE.—The upper view shows the controller and the lower view shows the reverser. The end boxes contain the motor cut-out switches and overload relay.

systems employing individual contactors. For example, the cam-shaft system has fewer parts subjected to wear ; it is less costly to maintain than an individual-contactor system ; a definite sequence of automatic contactor operations is obtained with a very small number of auxiliary contacts ; the control equipment is lighter, occupies less space, and can be inspected easier and quicker than a corresponding equipment with individual contactors. Moreover, the control-circuit wiring for automatic control is very much simpler than that for the corresponding system having individual contactors.

On account of these advantages—which are also common to the combined drum-controller and contactor system—the present tendency in the United States of America is towards the exclusion of individual-contactor control systems on motor-coach trains. Cam-shaft control

equipments are being adopted extensively in modern European direct-current electrification, and some manufacturers employ this system exclusively for railway control equipments.

We shall now consider typical cam-shaft control systems employing electro-pneumatic and all-electric operation.

Electro-pneumatic cam-shaft system. This system of control has recently been developed by the General Electric Co. (Schenectady), the British Thomson-Houston Co., and Messrs. Brown-Boveri. The motor-circuit connections are made by a group of cam-operated contactors, the cam-shaft being operated by differential air cylinders in a manner similar to the above pneumatically-operated drum controllers. The cams are,

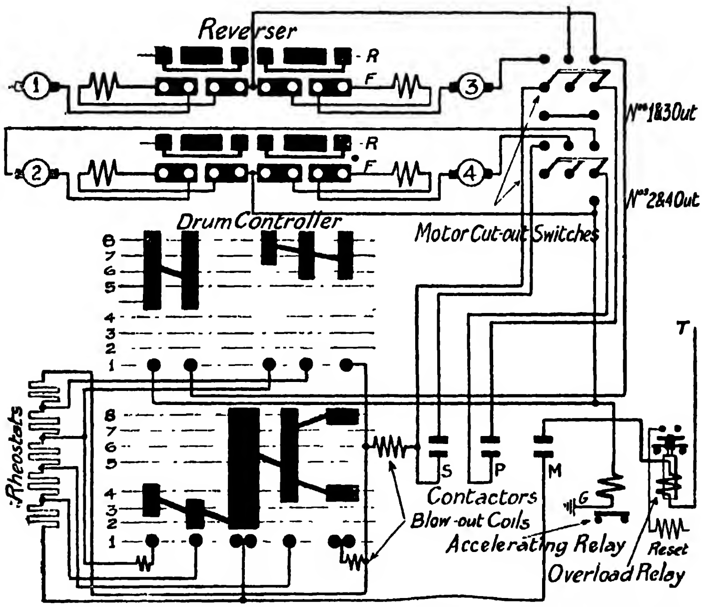


FIG. 158. -Main-circuit Connections of Westinghouse (Type HLD) Control Unit.

of course, insulated from the shaft, and certain sections of the cam-drum are insulated from one another.

Fig. 159 illustrates a G.-E. controller for the control of two 250-h.p. 600-volt motors arranged for mounting under the car. A large number of these controllers are in use on the Interborough Rapid Transit Railway, New York. The frame is divided into four compartments. The compartment *A* contains the cam-operated contactors, of which there are ten in the present controller ; the adjacent compartment, *C*, contains, in the front half, the relays for automatic control—comprising an accelerating relay, a line relay, and an electrically reset overload relay—and, in the back half, the interlocking drum for the cam-shaft. The differential air engine, *B*, is arranged between compartments *A* and *C*. The compartment *D* contains two pneumatically-operated contactors or circuit

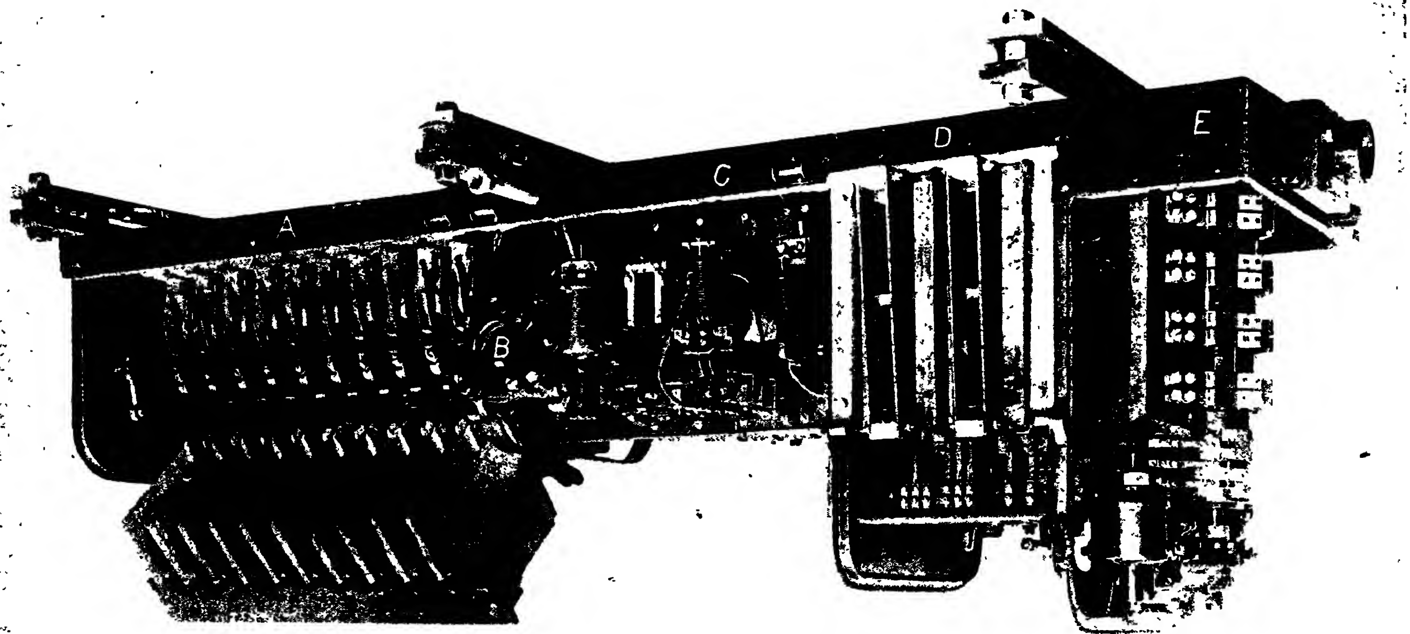


Fig. 150.—G.E. and B.T.-H. Co.'s Electro-pneumatic Control Unit arranged for Under-car Mounting.

Note.—The illustration shows the apparatus, with covers removed, in a position in which it is installed on the coach. The arc chutes of the contactors are lowered to show the latter.

breakers, while the end compartment, *E*, contains a pneumatically-operated drum-type reverser.

Each of the pneumatically-operated circuit breakers is provided with a separate arc chute and a powerful magnetic blow-out. In normal operation the motor circuits are broken by these circuit breakers; hence

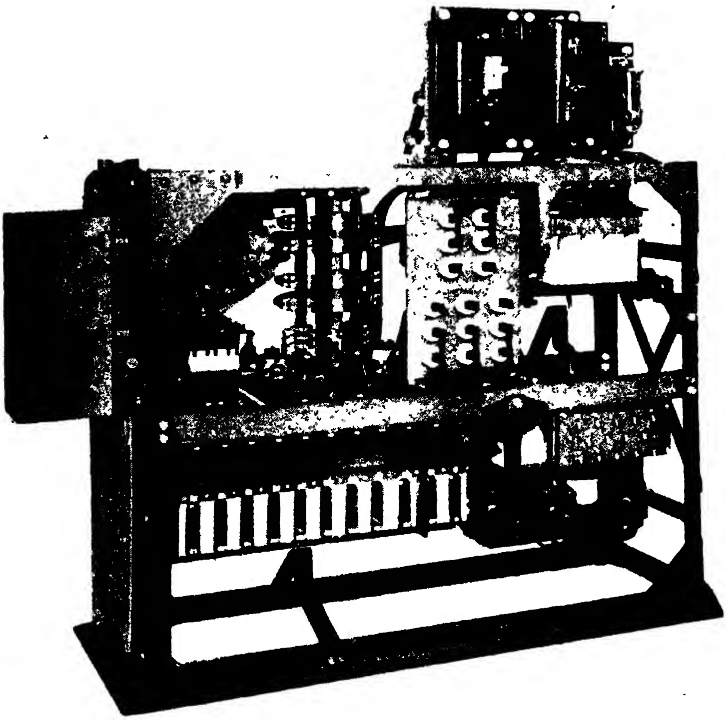


Fig. 160.—B.T.-H. Electro-pneumatic Control Apparatus for a Four-motor (1500-volt) Equipment.

the arcing which occurs at the contactor group is only that resulting from the changes in the motor and rheostat combinations.

Fig. 160 shows the B.T.-H. control apparatus for a four-motor, 1500-volt equipment arranged for mounting in the driver's cab. The cam-shaft controller occupies the lower compartment, the circuit breaker, reverser, cut-out switches, and field-tapping switches (a group of four cam-operated contactors) occupy the upper compartment. The three relays mounted on the top of the steel framework are: the field-tapping relay, the current-limit, or accelerating relay, and the potential or line relay.

The accelerating relay is of the pivoted armature type; its electrical circuits are shown in Fig. 161 and its action is described in detail later.

The field-tapping relay is for the purpose of ensuring that the operation

of the field-tapping switches shall take place only when the motor current is below a prescribed limit at which the change from full field to tapped field can be made safely and without the possibility of a flash-over. The relay is of the plunger type with a series operating coil.

Simplified diagrams of the main-circuit and control-circuit connections are given in Figs. 161, 162.

The **action of the cam-shaft controller** is similar to that of the electro-pneumatic drum controller described on p. 225, i.e. the controller is moved "on" by energizing both the "on" and "off" valve magnets, its motion is arrested by opening the circuit of the "off" valve magnet the "on" valve magnet remaining excited), and it is returned to the

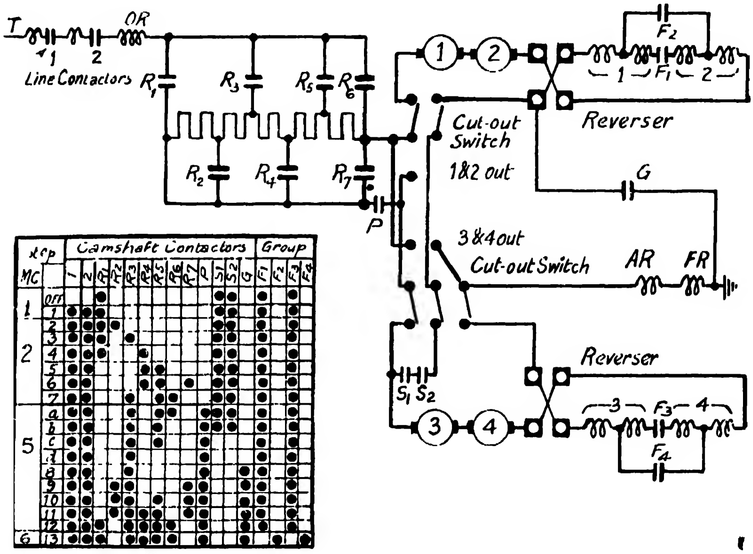


FIG. 161.—Main-circuit Connections for B.T.-H. Electro-pneumatic Camshaft Control System.

"off" or initial position by opening the circuits of both "on" and "off" valve magnets.

The **construction of the accelerating relay** differs considerably from that of the relays hitherto considered. The present relay has three pivoted armatures, three pairs of contacts, and four operating coils (viz., one series coil—which is connected in the motor circuit—and three shunt coils). It is provided with a "by-pass" or "advance" feature which, in conjunction with special operating positions and contacts on the master controller, enables the motor controller to be advanced one step independently of the value of the motor current.

The arrangement of the magnetic circuits and contacts is shown diagrammatically in Fig. 162. The armatures are spring biased to the positions shown in this diagram, these positions corresponding to no current in the operating coils.

The armature, *E*, and the contacts, *J*, form the accelerating relay proper. The armature is actuated by the series and shunt coils, *A*, *B*.

These coils and the restraining spring are so proportioned that the armature is attracted to the pole-piece F only when both coils are energized; but when attracted the armature is held in position by the current in the series coil alone, provided that this current is above the value which causes the armature to be released. This value of current is dependent upon the tension (which is adjustable) of the restraining spring.

The **by-pass feature** consists of the armatures G, H, the contacts K, L, and the shunt coils C, D. The magnetic circuits are so arranged that when the armatures are attracted to their respective pole-pieces by the energizing of both the coils C, D, they will be retained in position if

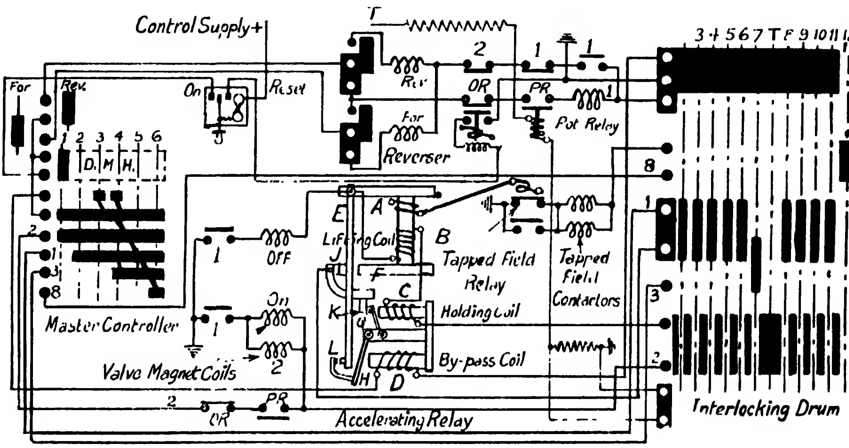


FIG. 162.—Control-circuit Connections for B.T.-H. Electro-pneumatic Camshaft Control System.

The interlocks marked 1, 2 are those of the "line" contactors. OR, PR denote the overload and potential relays respectively.

current is maintained in coil D only. The contacts K, L are connected in series with each other and in parallel with the contacts J.

Hence, when the armature, E, of the accelerating relay is held by the series coil, A, so as to interrupt (via the contact J) the circuit of the "off" valve magnet, and thereby stop the progression of the cam-shaft, the circuit of this valve magnet can be re-established by energizing the coil D (e.g. by moving the master controller to either of the "by-pass" positions). The cam-shaft therefore moves to the succeeding notch whatever the motor current may be. During the process, coil C is energized temporarily—by means of the "intermediate" contacts and fingers of the interlocking drum—thereby actuating armature G and opening the circuit of the "off" magnet at the contacts K. These contacts will remain open as long as coil D is energized, and therefore the cam-shaft is only advanced one step for each movement of the master controller to the "by-pass" positions. If a second movement of the cam-shaft is required, and the contacts J are open, due to a high motor current, the master controller must be returned to the normal operating position and advanced again to the appropriate "by-pass" position. It will be

observed that the accelerating relay proper can still control the " notching-up " of the motor controller if the master controller is retained in either of the by-pass positions.

The **Brown-Boveri power-operated cam-shaft controller** is built as a unit separate from the operating gear, and is adaptable to either electro-pneumatic or all-electric operation to meet the requirements of motor-coach and locomotive service.

The **electro-pneumatic operating mechanism** is shown diagrammatically in Fig. 163. It consists of differential air cylinders for operating the cam-shaft together with a pneumatically-operated ratchet wheel, or " position regulator." The object of the latter is to ensure an accurate setting of the cam-shaft at each operating position, thereby

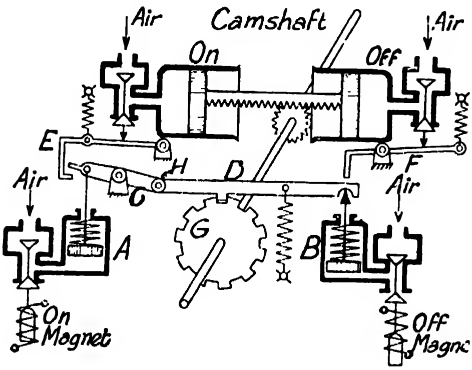


FIG. 163.—Arrangement of Electro-pneumatic Operating Mechanism of Brown-Boveri Camshaft Controller.

enabling a large number of steps to be provided with a cam-shaft of relatively small diameter.

The " on " and " off " valves controlling the differential cylinders are operated mechanically by tappets, which are actuated by auxiliary pneumatic cylinders, the air supply to which is controlled by electro-magnetic valves as in the preceding case.

The diagram shows the valves in the positions corresponding to equilibrium of the cam-shaft (i.e. balanced pressures on the differential pistons). Thus the " on " valve magnet is energized ; air is admitted to the left-hand auxiliary cylinder *A* (thereby lifting the striking end of the tappet-lever, *C*, clear of the tappet, *E*, of the valve controlling the " on " cylinder) ; the pawl, *D*, is engaged in a slot of the ratchet wheel, *G* ; the " off " valve magnet is not excited ; the right-hand auxiliary cylinder *B* is open to exhaust, and the tappet, *F*, of the valve controlling the " off " cylinder is clear of its operating lever, *D*. (NOTE.—The levers *C*, *D* are knuckle jointed at *H*.)

When the " off " valve magnet is energized in addition to the " on " valve magnet, air is admitted to the right-hand auxiliary cylinder *B*. The pawl *D* is lifted clear of the slot in the ratchet wheel and the lever then actuates the tappet, *F*, of the valve controlling the " off " cylinder, causing air to be released. The cam-shaft moves to the next " on " position, and during the process the circuit of the " off " valve magnet

is broken at the contacts of the interlocking drum (which is not shown in Fig. 163). Hence the air in cylinder *B* is exhausted, the pawl-lever, *D*, disengages the tappet *F*, causing the re-admission of air to the "off" cylinder, and the pawl engages with the next available slot in the ratchet wheel.

When power is cut off from both valve magnets, air is exhausted from the left-hand auxiliary cylinder, *A*. Lever *C* moves in the counter-clockwise direction, lifts the pawl clear of the ratchet wheel, and actuates the tappet of the valve controlling the "on" cylinder. The air in this cylinder is exhausted and the cam-shaft returns to the "off" position.

All-electric (English Electric Co.'s) system. The essential difference between this and the electro-pneumatic system is the method of operation. The cam-shaft is operated by a small electric motor and the reverser is

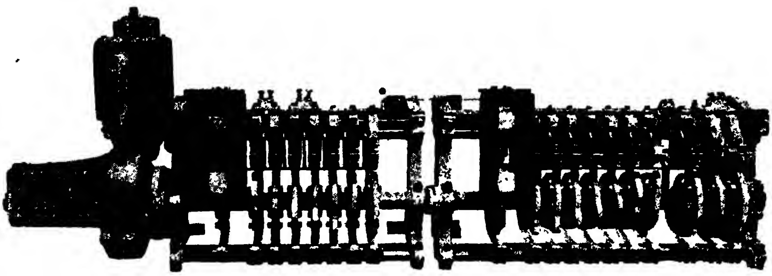


FIG. 164.—English-Electric Camshaft Controller for Locomotive.

operated by electromagnets. The line, or circuit-breaking, contactors are of either the electromagnetic or cam types, the latter being operated by cams fitted to an extension of the main cam-shaft.

Fig. 164 shows a typical **cam-shaft controller** with its driving motor and interlocking drum. This illustration refers to a controller for a 1500-volt locomotive. The cam shaft is driven through gearing by a direct-current, separately-excited, low-voltage, shunt motor, the starting and stopping of which is controlled by a contactor (called the "cam-shaft motor relay") mounted on the frame of the motor. The opening and closing of this contactor is governed by an interlocking drum (called the "position regulator") which is shown on the extreme left of the controller.

The reversing switch for the cam-shaft motor is fitted to the line, or circuit-breaking, contactors, and is so arranged that the motor cannot start in the forward direction until these contactors have closed, nor start in the backward direction (for moving the cam-shaft to the "off" position) until these contactors have opened. Hence the main circuit is always broken by the line contactors, and magnetic blow-outs are unnecessary except on the transition contactors (e.g. the "bridge" contactor when bridge transition is employed; the "series" and one rheostatic contactor when shunt transition is employed).

Fig. 165 shows the controller, reverser, and motor cut-out switches installed in a locomotive. Typical control equipments, for 600-volt and

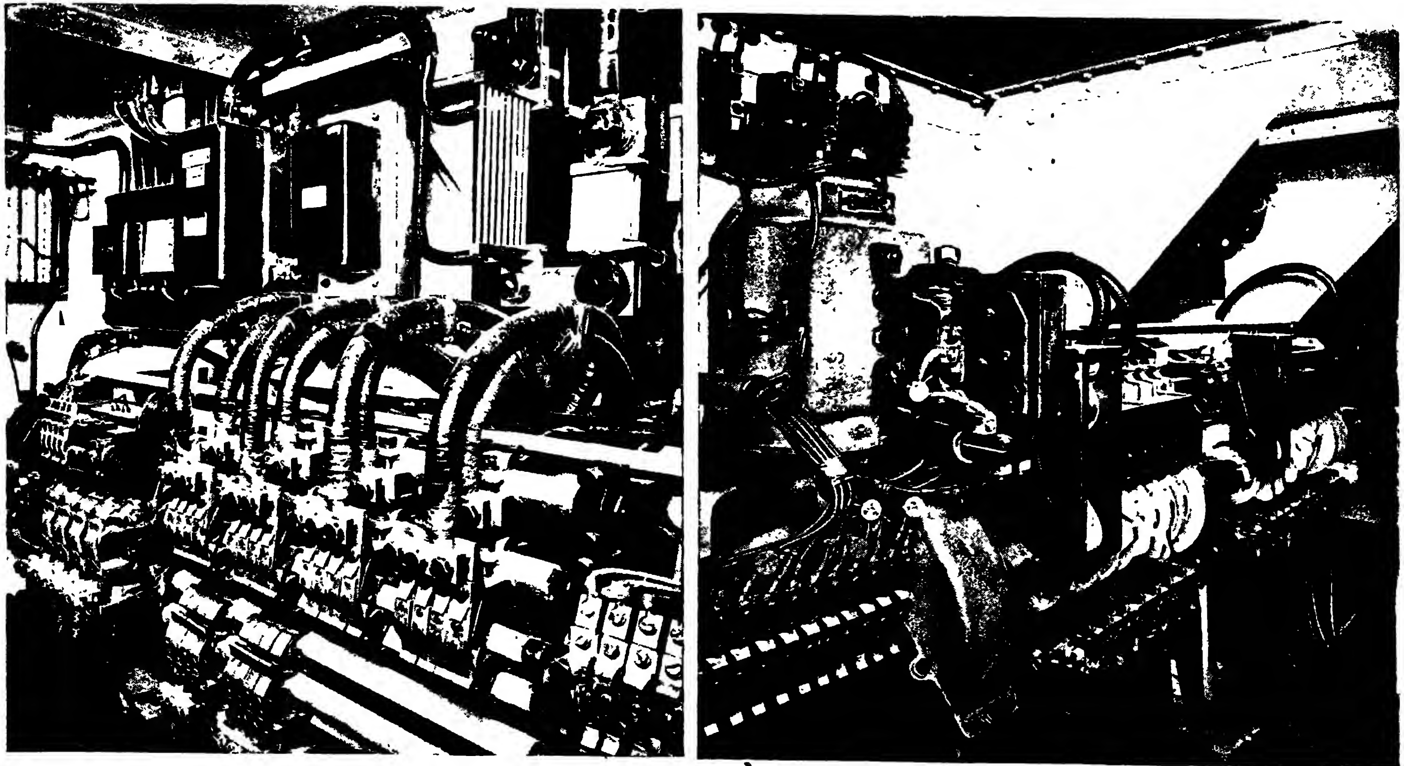


FIG. 165.—English-Electric Cam-shaft Control Equipment installed in Locomotive.

The right-hand view shows the cam-shaft controller (the position regulator, position relays, motor, and its controlling relay being shown in the foreground). The left-hand view shows the reverser, motor cut-out switches, ammeter shunts, etc.: this apparatus being mounted in line with and to the left of the position regulator.

1500-volt motor coach service, arranged for underframe mounting are illustrated in Figs. 166, 168.

The **600-volt equipment** illustrated in Fig. 166 comprises two cam-operated circuit-breaking contactors, *A*—the operating cams of which are fitted to an extension of the main cam-shaft, *B*—a small motor, *C*, which drives the cam-shaft through worm gearing, *D*; a "position-regulator" or interlocking drum, *E* (mounted between the gearing and the cam-shaft); a reverser, *F*; motor cut-out switches, *G*; the cam-motor relay, *H*; the current-limit or accelerating relay, *J*; an overload relay and two auxiliary ("position") relays.

The connections are shown in Fig. 167, from which we observe that the control is automatic and is provided with a "by-pass" or "advance" feature.

The operating link-work of the circuit breakers is of the toggle type, and the toggles are retained in their closed positions by electromagnets,

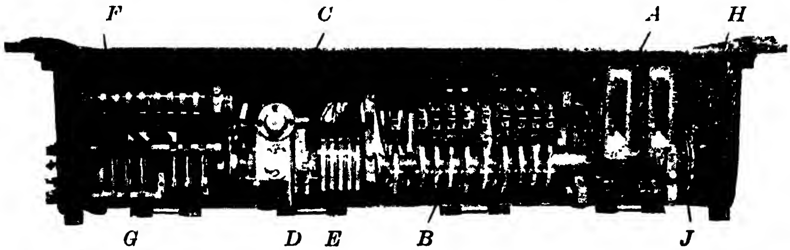


FIG. 166.—English-Electric 600-volt Cam-shaft Control Equipment for Motor-coach Service.

which are energized from the control circuit via interlocks on the reverser, cam-shaft, and overload relay. In normal operation the circuit breakers open when the master controller is returned to the "off" position, but they also open in the event of an overload or an interruption of the line voltage.

The **current-limit,** or accelerating, **relay** operates in conjunction with a special steel cam fitted to the end of the cam-shaft. The profile of this cam consists of a number of notches, each notch corresponding to an operating position of the cam-shaft. The pawl which engages with these notches carries one of the contacts of the relay, the other contact being attached to the pivoted armature. (These contacts control the cam-shaft motor relay.) The contacts, relay armature, and pawl are so arranged that when the pawl occupies a notch in the cam the contacts are closed if the relay armature is released, but are open if the armature is he'd up by the current in the operating coil (which is connected in the main circuit of one of the motors). When the cam-shaft advances (due to these contacts being closed), the pawl, together with the relay armature, is lifted by the cam (the contacts remaining closed), and, if the motor current is above the prescribed value for which the relay is set to operate, the armature is held while the pawl passes into the next notch in the cam. This operation opens the relay contacts, thereby interrupting the operating coil circuit of the cam-shaft motor relay, and stopping the motor. Observe that the cam-shaft motor is stopped by cutting off power from, and

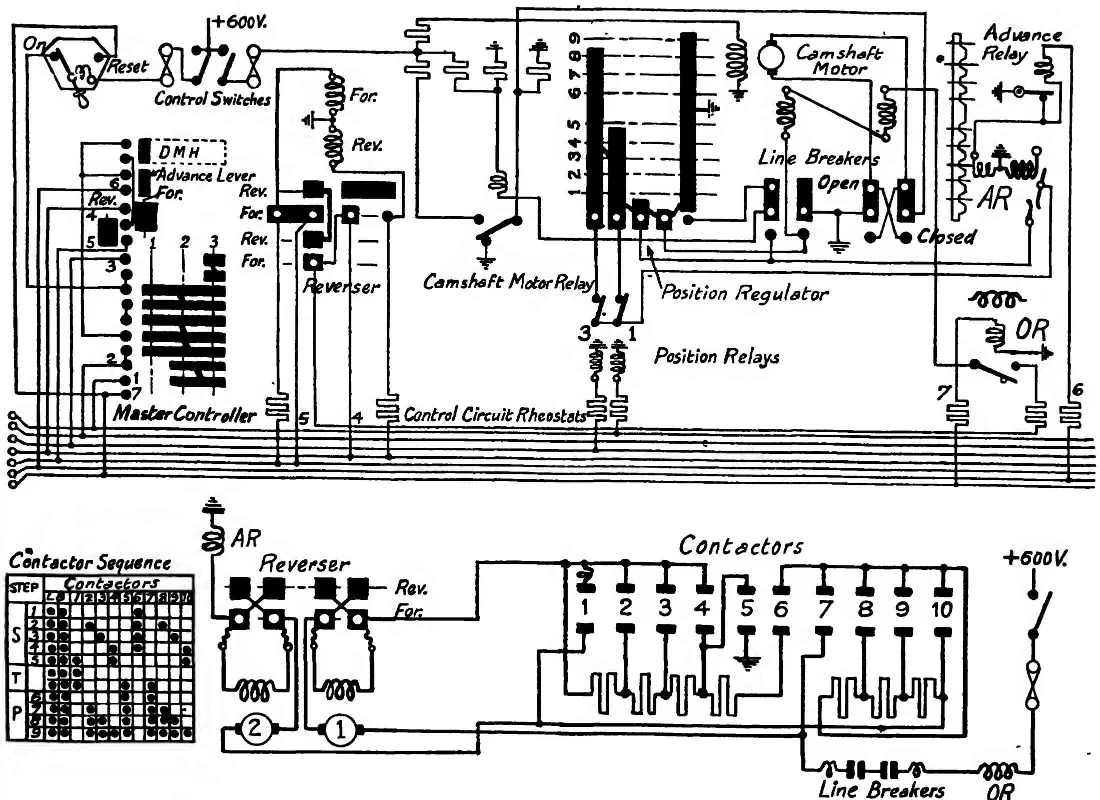


FIG. 167.—Connections of English-Electric 600-volt Cam-shaft Control System.
(The main-circuit connections are shown for a two-motor equipment.)

immediately short-circuiting, the armature, the field remaining excited. The cam-shaft motor will not again start until the circuit of its relay is re-established by the accelerating relay.

The "by-pass," or "advance" **feature** consists of a special lever

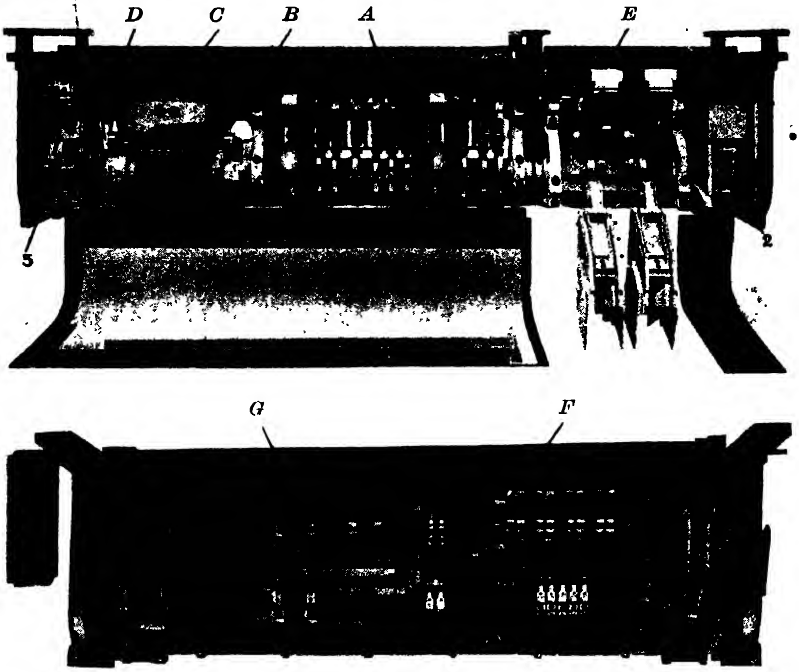
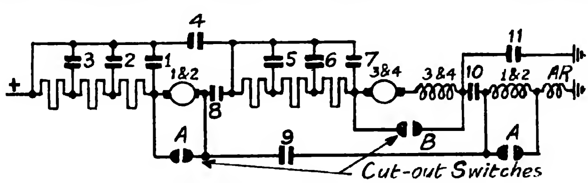


FIG. 168. -English-Electric 1500-volt Cam-shaft Control Equipment for Motor-coach Service.

The upper case contains the cam-shaft controller (*A*) together with its position-regulator (*B*), motor (*C*), and control relay (*D*); the line contractors (*E*); the overload and accelerating relays (2); and the "position" relays (5). The lower case contains the reverser (*F*); the motor cut-out switches (*G*); and the main and auxiliary isolating switches (located in the end compartments).



Schematic Arrangement of Main-circuit Connections for Fig. 169.

(spring-biased to the "off" position) and contacts on the master controller, together with an auxiliary relay and a demagnetizing shunt coil on the accelerating relay. When the lever is placed in the "advance" position, the auxiliary relay is energized and the lifting of its armature connects the operating coil in series with the demagnetizing coil of the

accelerating relay. The armature of the latter (if held up by a high motor current) is, therefore, released, and the cam-shaft is advanced one step.

The 1500-volt equipment, Fig. 168, also has cam-operated circuit-breaking contactors, but is arranged for either automatic or non automatic control; in consequence of which a greater number of "position" relays and contacts on the "position regulator" are necessary. The accelerating relay is separate from the cam-shaft; it is of the single-coil type, and provision is made for short-circuiting its contacts when non-automatic control is required. The control circuit is supplied at 120 volts from a motor-generator set, one set being carried on each motor coach. When two or more motor coaches form a train, the control-circuit supply may, if necessary, be obtained (by means of selector switches) from any motor-generator set on the train.

A simplified diagram of connections is given in Fig. 169.

CONTROL SYSTEMS FOR LOCOMOTIVE EQUIPMENTS

I. Low-voltage Double Series-parallel Control

General. A locomotive must be capable of operating under variable service conditions which may include shunting service as well as the hauling of trains of various weights at slow and moderate speeds. Moreover, the conditions at starting are of an entirely different nature to those relating to motor-coach operation. In the latter case a high acceleration is essential, and the starting period rarely exceeds 20 seconds. But with locomotive operation the acceleration must be limited to moderate values and the starting period may, under certain conditions, occupy several minutes. For example, in starting a long loose-coupled freight train, the initial tractive effort must be limited to a moderate value in order that the slack may gradually be pulled out of the couplings. This initial tractive effort must be increased by uniform increments until the normal accelerating tractive effort is reached. In passing from notch to notch the fluctuations in the tractive effort must be limited to relatively small values and must be uniform, both in order to avoid shock and to prevent slipping of the driving wheels.

To fulfil these conditions a large number of notches are necessary in the controller, and to provide the range of speeds necessary for the varied service conditions an equipment possessing at least three running speeds is required. A four-motor equipment and double series-parallel control is therefore necessary.

Control apparatus. This differs only in detail from that for motor-coach service. In view of the varied conditions under which a locomotive must be capable of operating, however, certain features are introduced into the present equipments which are not usually provided in motor-coach equipments. For example, the reverser usually takes the form of a group of contactors which are used for breaking the circuit. Again, the control is always carried out on the non-automatic principle and may be arranged on the multiple-unit system to enable two or more locomotives to be coupled together and controlled by one driver.

Typical connections for electromagnetic-contactor system. The main-circuit connections are shown in Fig. 170.

The **transition** from series to series-parallel is effected by short circuiting

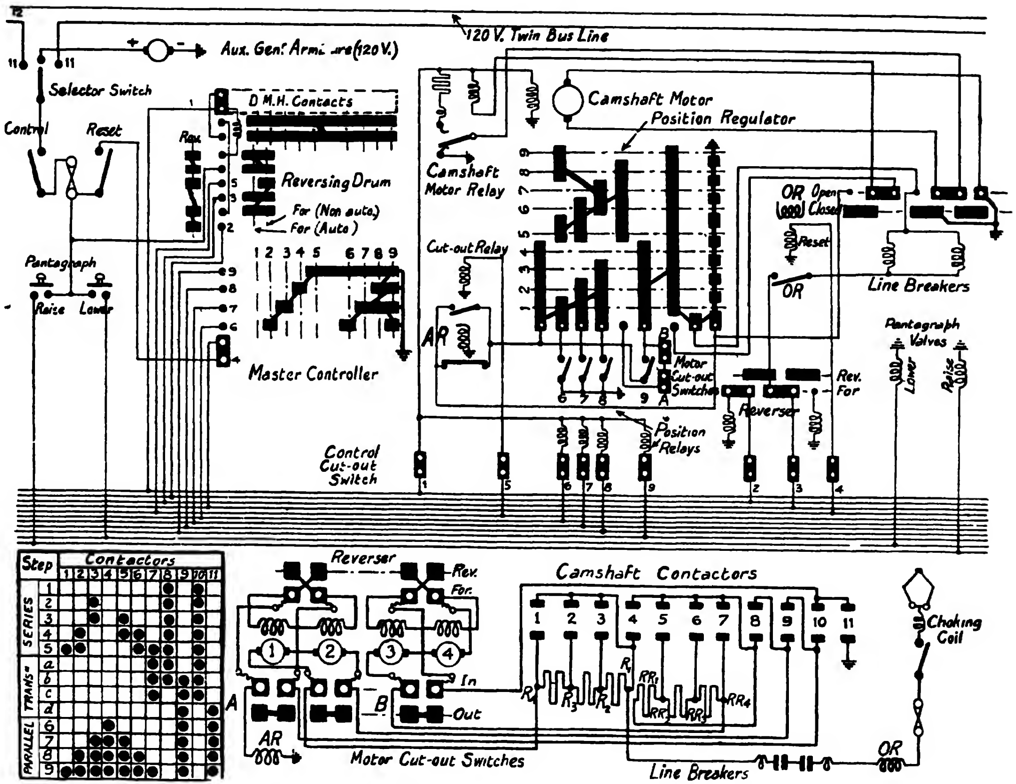


FIG. 169.—Connections of English-Electric 1500-volt Cam-shaft Control Equipment.

a pair of motors (Nos. 1 and 2), and the transition from series-parallel to parallel is effected by the " bridge " method.

Attention must be directed to the **method of grouping the motors and rheostats in the parallel notches.** At the completion of the transition period each motor is connected in series with its group of rheostats, the four groups of motors and rheostats being connected in parallel. On the second parallel notch two equalizing connections are established—by means of contactors Nos. 5 and 6—between motors Nos. 1, 3, and 2, 4 respectively, and the corresponding groups of rheostats. At the same time corresponding sections are cut out from rheostat groups Nos. 1 and 3. On the third, fourth, fifth, and sixth notches sections are cut out *alternately* from groups Nos. 2, 4 and 1, 3, respectively, and on the seventh (last) notch the remaining section in each group is cut out. This method of operation has two important advantages over the method in which the sections are cut out simultaneously from each group of motors ; first, fewer sections are required, and therefore the main wiring is simplified ; second, a large number of contactors—which would be required for the latter method—are eliminated, thereby effecting a considerable saving in cost, space, weight, and maintenance. Of course, with unequal resistances in the circuits of the two groups of motors the current input to one group will be greater than that to the other group, and consequently the tractive efforts exerted by the two groups of motors will not be equal. In practice, however, no disadvantage results from this method of operation.

Provision is made for cutting out a defective motor and operating the locomotive with the remaining motors. Under these conditions only the series-parallel and parallel notches of the controller are effective ; two motors being in circuit in the series-parallel notches, and three motors in the parallel notches. The four single-pole cut-out switches are arranged in two pairs, *A* and *B*, and the opening of one switch of a pair operates an interlocking switch in the control circuit which not only prevents the other motor of that pair being operated in the series and series-parallel positions of the controller, but also prevents the other pair of motors being operated in the series positions of the controller.

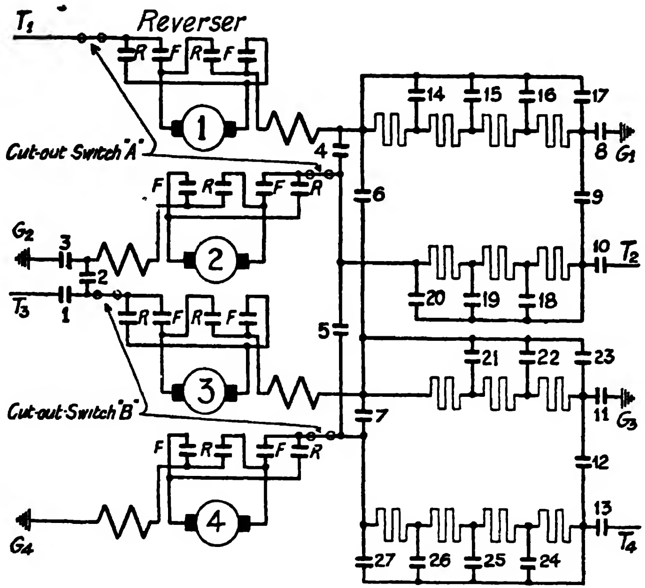
A simplified diagram of the **control-circuit connections** is given in Fig. 171, and a schematic diagram is included in order to facilitate the tracing of the circuits.

The operating coils of the reversers are not shown in the diagram ; they are arranged in four groups, each group containing four (" forward " or " reverse ") coils connected in series. The two groups of " forward " coils are connected in parallel, and supplied from wire No. 8, while the two groups of " reverse " coils are similarly connected and supplied from wire No. 0.

The interlocking switches—which are operated by the motor cut-out switches *A*, *B*—are shown in positions corresponding to the cut-out switches being closed (i.e. the full number of motors in circuit).

Of the **control-circuit operations** occurring on the 24 notches of the master controller, we shall only refer to those which possess features of interest.

On the first series notch wire No. 1 is energized, thus closing the reversers and contactors Nos. 2, 9. The closing of No. 9 removes the



NOTCH		Contactors 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
SERIES	1		●							●			●															
	2		●							●			●						●			●		●				
	3		●							●			●					●	●			●		●				
	4		●							●			●		●			●	●			●		●	●			
	5		●							●			●		●			●	●	●		●	●	●	●			
	6		●							●			●		●	●		●	●	●		●	●	●	●	●		
	7		●							●			●			●	●	●	●	●		●	●	●		●	●	
	8		●		●					●			●			●	●	●	●	●		●	●	●		●	●	
	9		●		●					●			●					●			●			●				●
SERIES-PARALLEL	10	●		●						●			●											●				
	11	●		●						●			●					●						●				
	12	●		●		●	●			●			●		●			●						●	●			
	13	●		●		●	●			●			●		●			●	●			●		●	●			
	14	●		●		●	●			●			●		●	●		●	●			●		●	●	●		
	15	●		●		●	●			●			●		●	●		●	●	●		●	●	●	●	●		
	16	●		●		●	●			●			●		●	●	●	●	●	●		●	●	●	●	●	●	
	17	●		●	●			●																				
PARALLEL	18	●		●					●		●	●		●														
	19	●		●		●	●		●		●	●		●	●										●			
	20	●		●		●	●		●		●	●		●	●				●			●			●			
	21	●		●		●	●		●		●	●		●	●	●			●			●		●	●	●		
	22	●		●		●	●		●		●	●		●	●	●			●	●		●	●		●	●		
	23	●		●		●	●		●		●	●		●	●	●	●		●	●		●	●		●	●	●	
	24	●		●					●		●	●		●			●	●		●	●		●	●			●	●

Fig. 170.—Main-circuit Connections for B.T.-H. Double Series-parallel Control System.

short-circuit from the operating coil of No. 12 and cuts this coil into the circuit of Nos. 2 and 9. The four motors are therefore connected in series with the whole of the rheostats.

The operations on the intermediate series notches are quite simple and can be followed without difficulty by the aid of the schematic diagram.

On the last series notch (No. 9) contactors Nos. 27, 20 are connected in series with Nos. 17, 23 and the circuits of Nos. 15, 16, 18, 19, 21, 22, 25, 26 are opened, thus leaving contactors Nos. 2, 4, 9, 12, 17, 20, 23, 27 closed.

Transition to series-parallel is effected, at the master controller, by energizing wires Nos. 2, 6, and opening the circuit of wire No. 16, thus causing the following operations to take place—

Contactors Nos. 27, 20, 17 open, due to the opening of the circuit of No. 16 wire, but contactor No. 23 remains closed, due to the retaining circuit formed by No. 6 wire. As soon as No. 27 opens, its interlocks complete the circuit of No. 1 contactor which is energized from No. 2 wire. The closing of No. 1 opens No. 2, and the opening of the latter completes the circuit of No. 3. When this contactor closes, its operating coil is connected—by means of interlocks on the contactor—in series with that of No. 1. Thus on the first series-parallel notch (No. 10) the following contactors are closed: Nos. 1, 3, 9, 12, 23.

The operations on the intermediate series-parallel notches do not require comment.

On the last series-parallel notch (No. 17) all the " rheostat " contactors are opened and the " bridge " contactors (Nos. 6, 7) are closed.

Transition to parallel is effected, at the master controller, by energizing wire No. 4, which causes the " line " and " ground " contactors (Nos. 10, 13, 8, 11) to close. The closing of No. 13 opens the circuit of Nos. 4, 7, thus completing the transition and giving the first parallel notch. The control-circuit operations occurring on the remaining parallel notches do not require comment, as the main-circuit operations have been discussed above.

If either of motors Nos. 1 and 2 is cut out, the interlocking switch actuated by the cut-out switch *A* opens the circuits of contactors Nos. 2, 5, 6; short-circuits the operating coil of No. 4; and prevents Nos. 17, 23 being energized from wires Nos. 6 and 7, but allows these contactors to be energized from the circuit of Nos. 20, 27 (wire No. 16). Hence, if motor No. 1 is cut out, No. 2 cannot be operated until the master controller is moved to the first parallel notch (No. 18) and contactor No. 10 is closed. Motors Nos. 3 and 4, however, can be operated in the series-parallel and parallel notches of the controller.

If either of motors Nos. 3 and 4 is cut out, the interlocking switch actuated by the cut-out switch *B* opens the circuit of contactors Nos. 5 and 6; short-circuits the operating coil of No. 7; and allows contactors Nos. 17, 23 to be energized only from the circuit of Nos. 20, 27. Hence the remaining motor of this pair can only be operated in the parallel notches of the controller, while motors Nos. 1 and 2 cannot be operated in the series notches of the controller.

The control system is adapted for the multiple-unit operation of two or more locomotives by providing the necessary coupler sockets, connection boxes, etc.

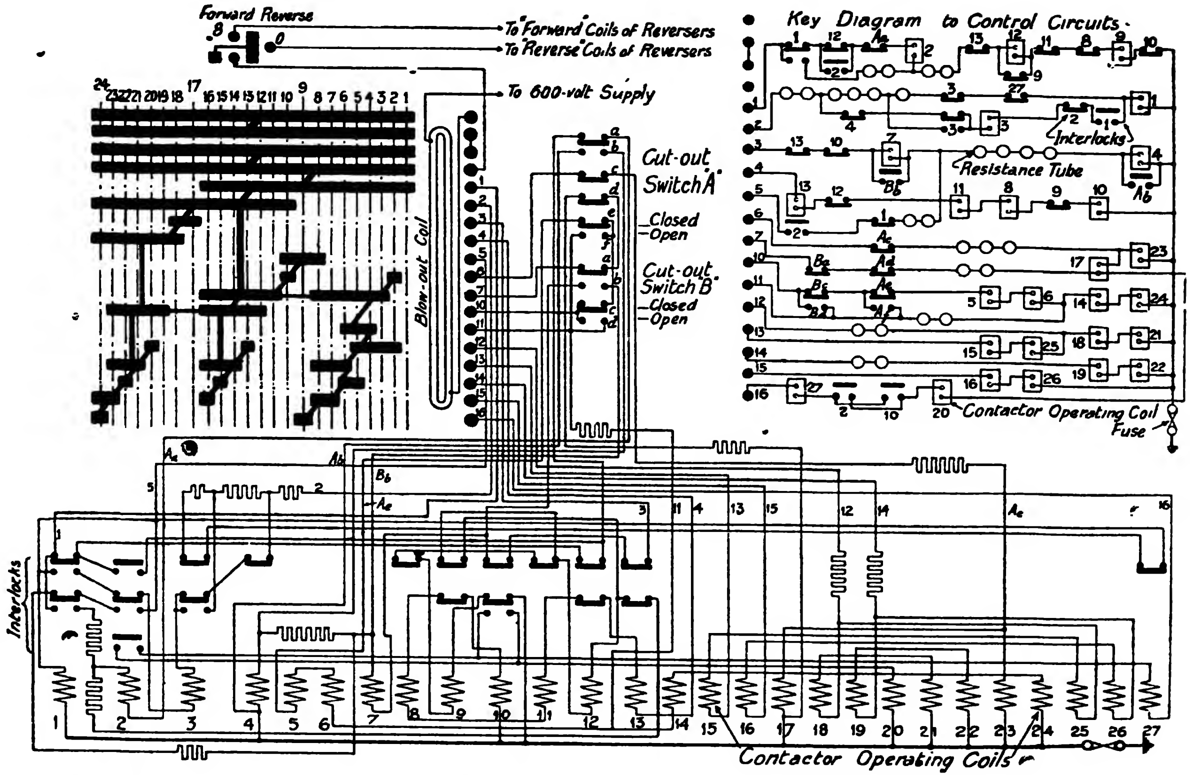


FIG. 171.—Control-circuit Connections for B.T.-H. Double Series-parallel Multiple-unit Control System.

NOTE.—The interlocks are shown in the "open" position of the contactors. When contactors close, the short-circuiting bridges of interlocks move downwards. The coupler sockets, connection boxes, etc., are not shown.

II. High-Voltage Series-Parallel and Double Series-Parallel Control

These equipments possess a certain number of special features. Thus, (1) a low voltage is necessary for the control circuit (the supply being obtained either from a battery, a motor-generator set, or a rotary transformer); (2) the connections must be so arranged that the field windings of all the motors forming a series-parallel, or double series-parallel, group are connected to the earthed side of the system; (3) the contactors at which current is broken require special arc chutes and magnetic blow-out; (4) overload protection should preferably be effected by a special form of quick-acting, or high-speed, circuit breaker in order to prevent "flashing" of the motors; (5) the isolating switch—which is for the purpose of disconnecting the main circuits from the line when inspections of the control equipment are being carried out—must be interlocked with the doors of the compartment containing the motor-controller so that these doors cannot be opened unless the isolating switch is open, and that the isolating switch cannot be closed when the doors are open.

Control-circuit supply. The control circuit, together with the train lighting and other auxiliary circuits, is supplied usually at a voltage of about 100–120 volts from a motor-generator set of special design. In some cases a rotary transformer or a reducer is employed. These machines are discussed later (Chap. XIII).

Motor combinations. With line voltages above 1500 volts, two or more motors are connected permanently in series, and, for control purposes, are considered as equivalent to a single motor. Both series-parallel and double series-parallel control are employed, the former being used for locomotives of moderate weight and the latter for heavy locomotives. Formerly heavy locomotives were equipped only for series-parallel control in order both to simplify the control apparatus and to reduce the number of contactors. But with the development of cam-operated contactors and more efficient magnetic blow-outs for high-voltage circuits, these locomotives are now equipped for double series-parallel control.

Transition is usually effected by the shunt method, as the total number of contactors required for control is then smaller than that required when bridge transition is adopted, although the number of contactors involved in the transition is greater with the former method. Considerable simplification of the control gear is possible by arranging the contactors effecting the combinations of the motors as a cam-operated group controlled electro-pneumatically, typical examples for series-parallel and double series-parallel control being shown in Fig. 172.

Shunt transition also enables all the field windings to be arranged on the earthed side of the system. This arrangement is advantageous for high-voltage circuits, as the reverser and field-tapping contactors may be of the low-voltage type. Moreover, as these switches and the field windings are subjected only to low voltages, the possibility of insulation breakdowns is eliminated.

Contactors. The special features of individual circuit-breaking contactors for high-voltage (3000-volt) circuits are (1) the insulation, (2) the magnetic blow-out and arc chute.

Typical individual contactors are illustrated in Fig. 173. Both the

fixed and moving contacts are insulated to enable two or more contactors

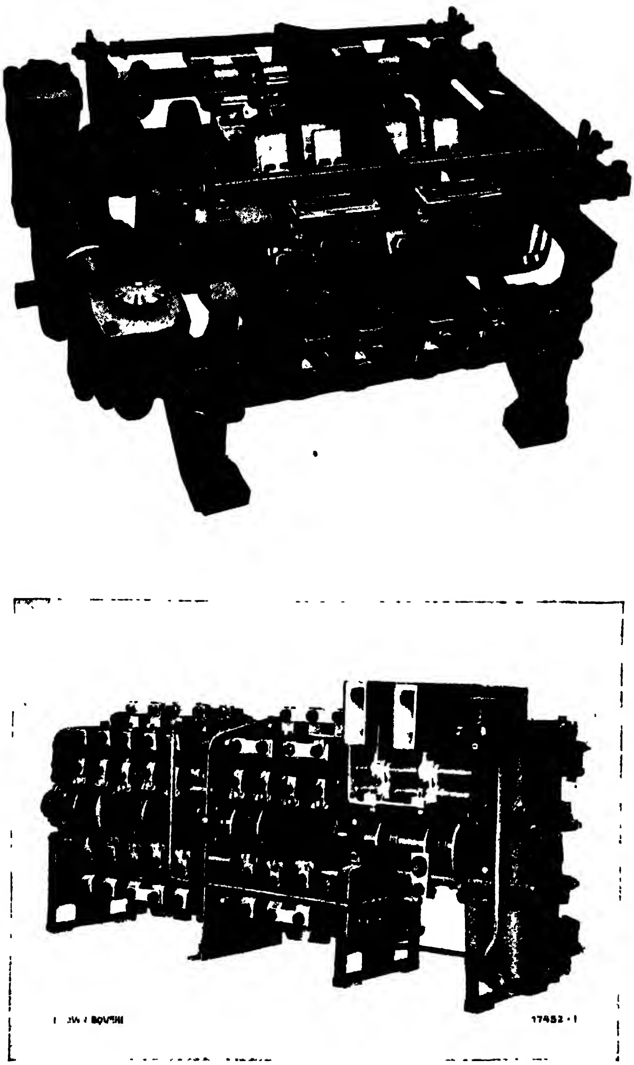


FIG. 172.—Cam-operated Contactor Groups for Changing Combinations of Motors.

Upper Illustration.—Metropolitan-Vickers cam group for series-parallel control.
Lower Illustration.—Brown-Boveri cam group for double series-parallel control.

to be connected in series when necessary. A strong blow-out field and a large narrow arc chute are provided for the suppression of the arc. The narrow arc chute is much more effective than a wide chute on account of the arc stream being brought more into contact with the sides of the chute and being thereby cooled more rapidly. In some cases a transverse

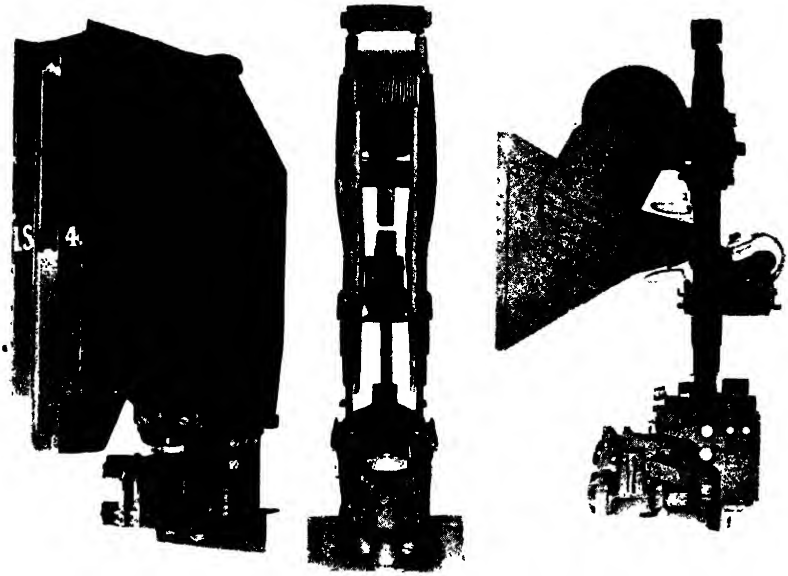


Fig. 173A. Metropolitan-Vickers Electro-pneumatic Contactor for 3000-volt Circuits.

[Views showing (1) the complete contactor, (2) front and side of contactor with arc chute removed.]

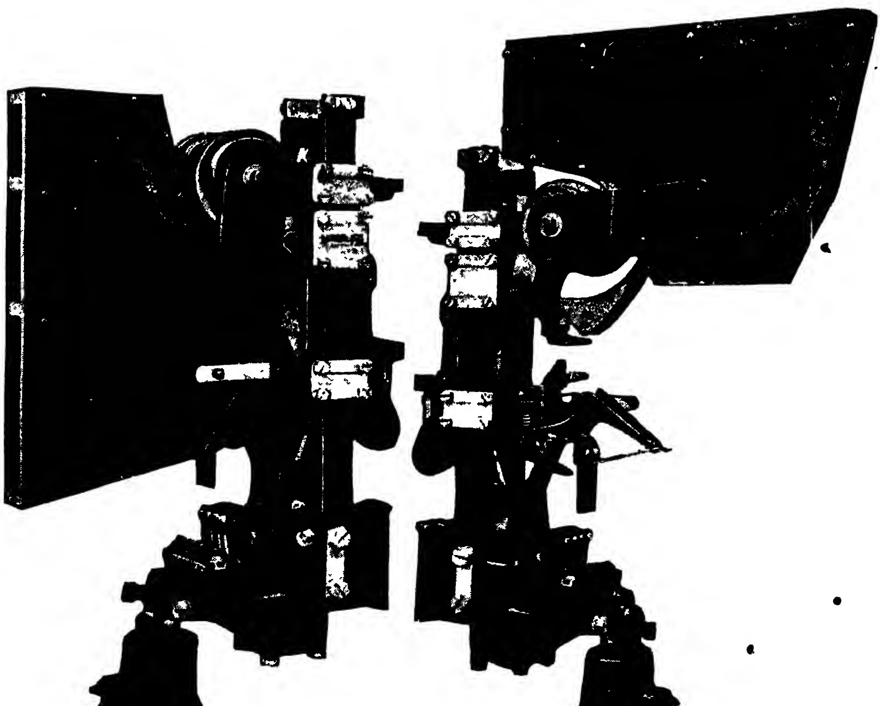


Fig. 173B.—General Electric-Oerlikon Electro-pneumatic Contactor for High-voltage Circuits.

barrier (called an "arc-splitter") is inserted in the arc chute for the purpose of increasing the cooling surface exposed to the arc stream.*

Example of series-parallel control for 3000-volt locomotive. This example refers to a 1200-h.p. locomotive with Metropolitan-Vickers equipment. The electro-pneumatic unit-switch control system is employed and is arranged for regenerative braking, but the consideration of the regenerative-control features will be deferred for the present. Individual contactors, or unit switches, are used for the rheostatic steps and at other positions in the circuit where current has to be broken.

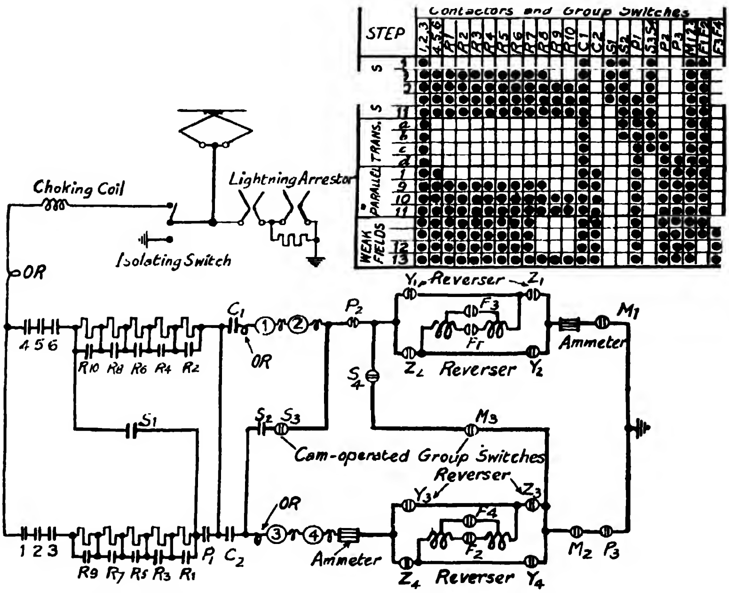


FIG. 174.—Main-circuit Connections for Series-parallel Control of 3000-volt Locomotive Equipment (Metropolitan-Vickers).

[NOTE.—The switching operations on the rheostatic steps 2–8, inclusive, involve closing in successive order, contactors R_1–R_7.]

But cam-operated contactor groups are employed for changing the motor combinations, field tapping, and reversing, as well as for changing over the main-circuit connections from "motoring" to "generating."

A simplified diagram of the main-circuit connections is given in Fig. 174.

The control is, of course, non-automatic, and, on account of the regenerative features, the master controller has three operating handles and contact drums (viz. the combined reversing and motor-combination drum, the braking drum, and the rheostatic or accelerating drum), as shown in Fig. 175.

* Comprehensive data of magnetic blow-outs, together with photographs of arc streams, are given in a paper and discussion on "Air-break magnetic blow-outs," by J. F. Tritle. *Trans. A.I.E.E.*, XLI, 262–287.

In operation the combined reversing and motor-combination handle is thrown to the "forward series" position and the accelerating handle is notched up to the full-series or weak-field position (tapped-field operation being possible with both combinations of the motors). Next the combined reversing and motor-combination handle is moved into the "forward parallel" position, and the accelerating handle is returned to the first notch, which causes transition to be effected automatically. The handle is then notched-up to the running position desired.

The manner in which transition is effected is as follows—

When the accelerating handle is returned to the first notch—the motor-combination handle being set for "forward parallel"—the opening of contactor R_1 energizes the "parallel" valve magnet of the pneumatic

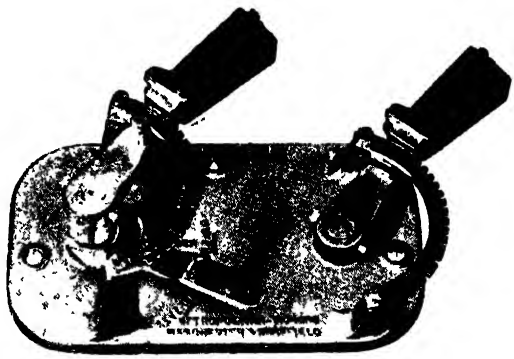


FIG. 175.—Cap-plate and Operating Handles of Metropolitan-Vickers Master Controller for Locomotive.

cylinders of the motor-combination cam-contactor group. As soon as contactor P_2 of this group closes, the circuits of the "parallel" valve magnet and the valve magnet of contactor S_2 are broken at the interlocking drum. When S_2 opens, the "parallel" valve magnet of the cam group is again energized—by means of interlocks on S_2– and the transition is completed by (1) closing contactor P_3, (2) opening contactors S_3, S_4, and (3) energizing the valve magnets of contactors LS_4, LS_5, LS_6, C_2, the latter operation being effected by the interlocking drum of the cam group.

The valve-magnet coils of all the rheostatic contactors are connected to a special set of interlocking contacts under the control of an auxiliary relay, the magnet-coil of which is in circuit with the auxiliary contacts of the three overload relays. Hence the operation of any of the overload relays cause the whole of the rheostatic contactors to open, and in consequence the whole of the starting resistance is inserted before the line contactors open, the latter operation being effected by interlocks on contactor R_1. In this manner the arcing at the line contactors is much less severe than it would be if these contactors were opened directly by the overload relays.

Examples of double series-parallel control for 1500-volt locomotives. One example refers to a 4000-h.p. locomotive with Brown-Boveri equipment, the locomotive being in service on the Paris-Orleans Railway. The control system gives twelve rheostatic steps and five running steps for each combination of the motors, four of the latter being obtained by field weakening.

Cam-operated contactors are used for the rheostatic and weak-field steps, and also for re-grouping the motors and rheostats, but drum-type switches are used for reversing and for changing the main-circuit connections for regenerative braking.

The cam-shafts of the main contactor groups (of which there are two) are chain driven from a low-voltage direct-current motor, but the cam-shaft of the re-grouping contactors is operated by a four-cylinder air motor with electrically-controlled valves (Fig. 172). This cam-shaft has three operating positions; the extreme operating positions are obtained by the separate use of two air cylinders, and the central position is obtained by the use of the other two cylinders.

Overload protection is obtained by a special circuit breaker which is closed by electro-pneumatic cylinders and is held closed by a latch which can be tripped by an overload coil. As the normal rating is 2100 A. the main contacts are of the brush type and are provided with secondary contacts (fitted with blow-out coils) and also two pairs of arcing contacts, which are arranged so as to insert resistance into the circuit before the final break occurs.

The simplified main-circuit connections are shown in Fig. 176. The shunt method of transition is adopted, and the exciting-field windings are all connected on the earthed side of the system. The commutating-pole windings (which are not shown in Fig. 176) are, however, connected adjacent to the appropriate armatures.

The second example refers to a 2250 h.p. locomotive with General Electric-Oerlikon equipment, the locomotive being one of the trial passenger locomotives for the Great Indian Peninsula Railway. In this case the motor equipment consists of three twin-motors (Fig. 33), each of which is designed for the line voltage (1500 volts). The three combinations of the motors—viz., series, series-parallel (each series group consisting of the two elements of one twin-motor and one of the elements of another twin-motor), parallel—therefore give running speeds in the ratio of 1 : 2 : 3, instead of 1 : 2 : 4, as in the first example.

A simplified diagram of the main-circuit connections is shown in Fig. 177, from which it will be observed that (1) two steps of shunted-field control—using inductive shunts, Fig. 177A—are employed for each combination of the motors; (2) the motor and control equipment is arranged in two halves. Electro-pneumatic contactors, Fig. 173B, are used throughout.

The reversers are of the drum type. Each has an "off" position, which is used for cutting-out a defective motor, segments being provided in this position of the drum to interconnect the extreme fingers shown in Fig. 177.

One of the inductive shunts is illustrated in Fig. 177A. It consists of a laminated-iron core with air gaps and a magnetizing winding, the latter being connected in series with a grid rheostat as shown in Fig. 177.

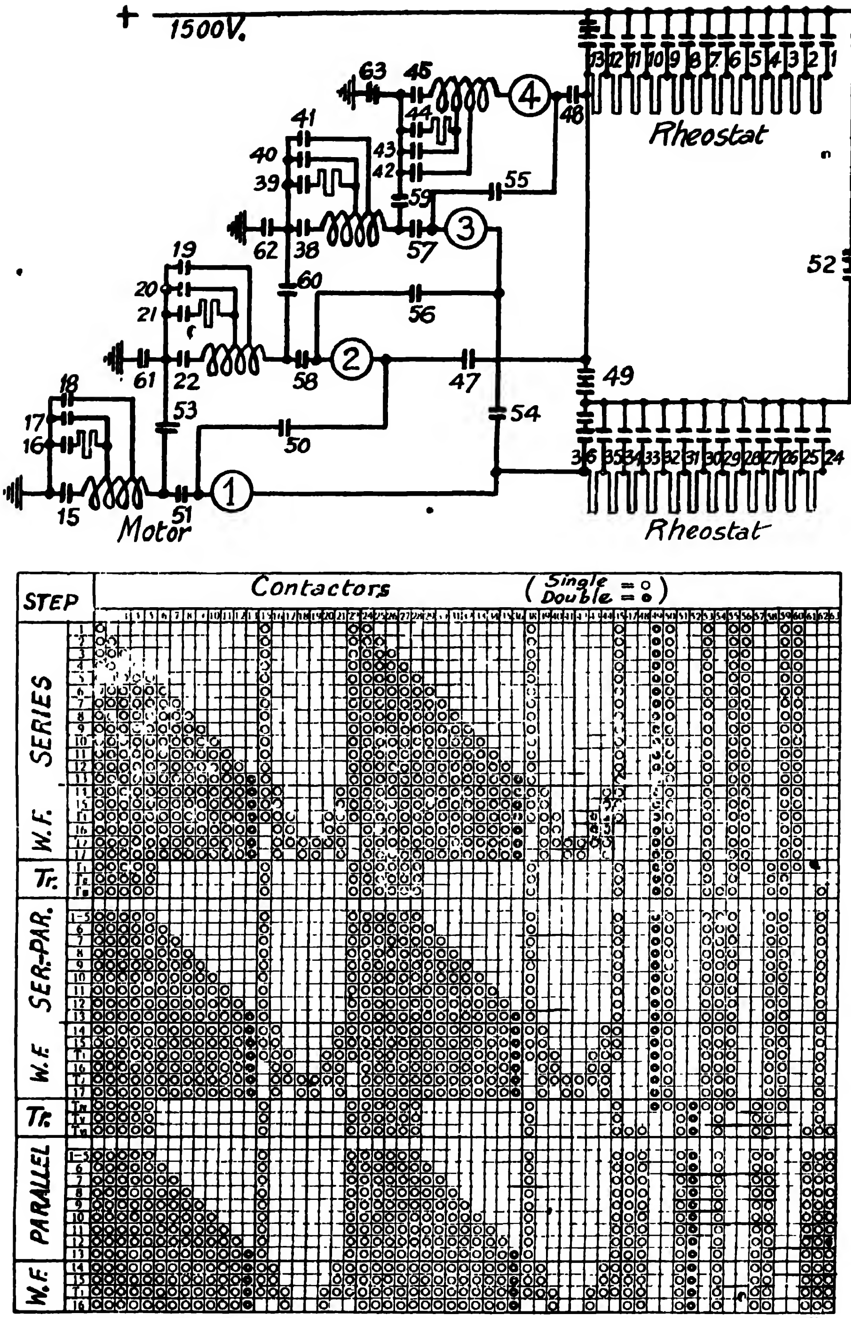


FIG. 176.—Main-circuit Connections for Double Series-parallel Control of 1500-volt Locomotive Equipment. (Brown, Boveri & Co.)

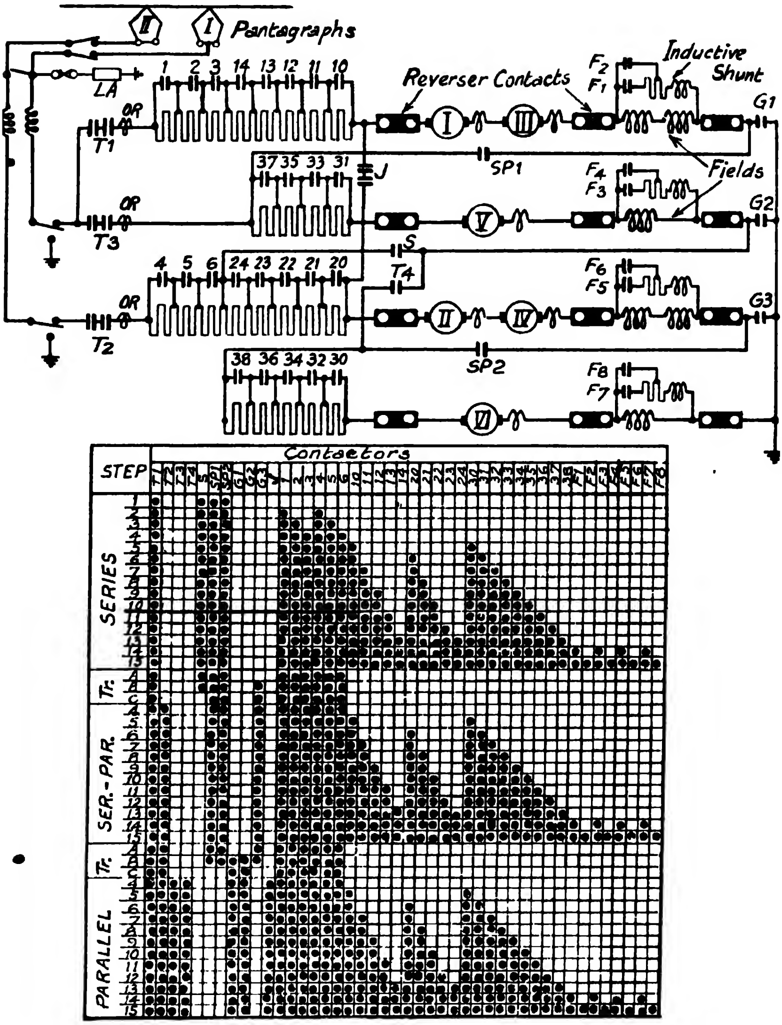


FIG. 177.—Main-circuit Connections for Double Series-parallel Control of 1500-volt Locomotive Equipment. (General Electric Co.).

CONTROL EQUIPMENTS FOR DUAL-VOLTAGE OPERATION

In an extensive scheme of electrification (which includes both suburban and main lines) two operating voltages may be necessary, viz. 600 or 1500 volts for the suburban lines, and 1500, or in some cases 3000, volts for the main lines. If the main-line trains operating to or from a given terminus have to run, without speed restrictions, over the same tracks as the suburban trains, then either the distributing system on these tracks must be duplicated, or the main-line train equipments must be arranged for dual-voltage operation. The latter alternative is usually

less expensive than the former. Such dual-voltage equipments are also necessary for any extensive interurban electric railway which includes "through" running over the "local" tracks of city tramways, as the normal voltage of the interurban system would be 1200 or 1500 volts, while that of the local tramway systems would be 600 volts.

We shall consider briefly how dual-voltage operation affects the

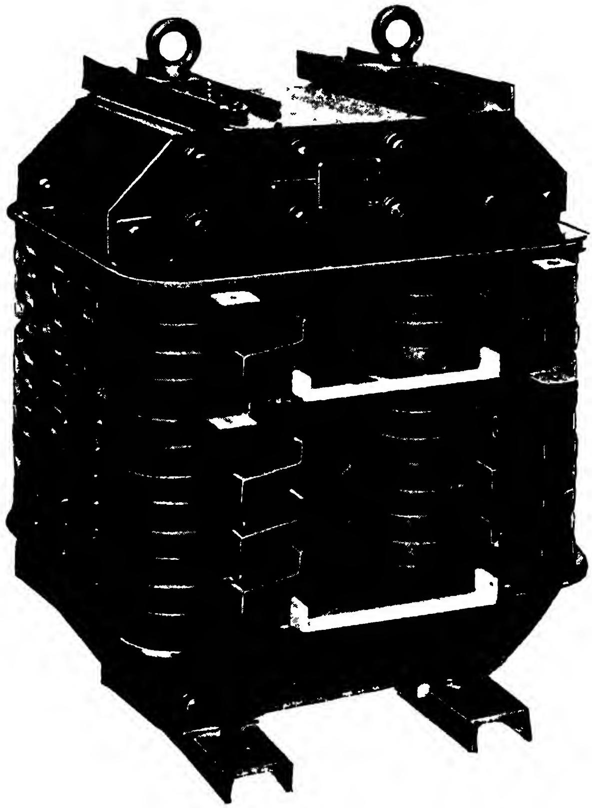


FIG. 177A.—General-Electric Inductive Shunt for Shunted-field Control.

control equipment. The simplest case is when the two voltages are in the ratio of 2 : 1.

If half-speed operation on the low-voltage system is permissible, the only change involved (other than the change of current collectors, if necessary) in passing from the high-voltage to the low-voltage system, or vice versa, is in the control-circuit supply. But this change over may be avoided if the control circuit is supplied from a battery or a specially-designed motor-generator set.

If, however, full-speed operation on both voltages is required, change-over switches are necessary for both the motor portion and the rheostat portion of the main circuit.

The normal operating voltage of each motor must be equal to that of the low-voltage system. Hence for series-parallel control at least four motors are necessary for each " unit " of the train or locomotive equipment. Therefore a change-over switch is required for each pair of motors to change their connections from series to parallel, or vice versa, when changing the operating voltage. A change-over or re-grouping switch is also necessary for cutting out or series-paralleling certain sections of the starting rheostat in order to obtain suitable grading for each operating voltage.

APPENDIX TO CHAPTER IX

THE CALCULATION OF STARTING RHEOSTATS FOR DIRECT-CURRENT MOTORS

General Considerations. A reference to the connection diagrams of series-parallel controllers will show that the starting rheostats must be arranged with a limited number of sections, and that some of the sections must be suitable for use with both the series and the parallel positions of the controller. The number of sections for use with a given motor equipment is governed by (1) the maximum tractive-effort which may be exerted during the starting period; (2) the permissible variation of the tractive-effort. These considerations involve others, such as the adhesive weight of the train, locomotive, or car; the coefficient of adhesion; the mass to be accelerated; and the gradients (if any) which have to be negotiated.

With tramcars the adhesive weight is from 75 per cent to 100 per cent of the weight of the car, while with motor-coach trains the adhesive weight is usually of the order of 50 per cent of the weight of the train. Generally, in each of these cases, the mean accelerating tractive-effort during starting is much below that required to slip the driving wheels under normal conditions (i.e. with dry rails). Therefore, relatively large fluctuations in the tractive effort are permissible, so that only a few notches are required on the controller.

On the other hand, with electric locomotives, the tractive-effort required for acceleration may approach the limiting value at which slipping of the driving wheels occurs; and in this case only a relatively small variation of the tractive-effort is permissible during starting, so that a large number of notches will be required on the controller.

We shall show that the number of sections and also the resistances of the sections are both influenced by the slope of the speed curve between the limits of current during starting. In general, a motor possessing a steep speed curve (e.g. a single-phase motor, or a direct-current motor with either an unsaturated magnetic circuit or a high internal resistance) requires fewer rheostat sections (for a given percentage variation of tractive-effort) than a motor possessing a flat speed curve.

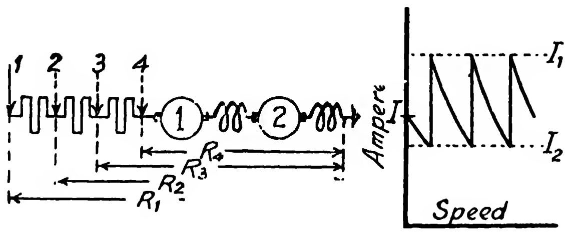
The data required for the calculation of the number of sections and the resistances of the sections are: the speed and tractive-effort curves of the motor (corresponding to the line voltage at which the start is to be made); the resistance of the motor; the limiting value of the tractive effort and the permissible variation of tractive effort during starting. The calculations involve the use of *two* coefficients—which are called " grading coefficients "—viz. the ratio of the lower and upper limits of the current during starting and the ratio of the tangents of the magnetization curve at these currents. They cannot, therefore, be effected without a knowledge of the magnetization

curve (or, alternatively, the speed curve of the motor. It is this fact that renders the calculations more complicated than those for the starting rheostat for a shunt motor (in which only one coefficient is involved).

The simplest solution is obtained by deriving a second relationship between the coefficients in *general terms* (i.e. independent specifically of any particular motor), as with two relationships available, each of the two coefficients can be determined without difficulty.

The method is best explained by deducing from first principles, and in general terms, the equations relating to the starting period.

Calculation of resistances of sections for series steps. Consider a single starting rheostat to be connected in circuit with two motors as shown in the circuit diagram of Fig. 178 (*a*). Let n denote the number of sections in the rheostat; $(n + 1)$ the number of steps or notches in the series position of the controller; $R_1, R_2, \ldots R_n, R_{n+1}$, the resistances of the circuit on each of the several notches; R_m the resistance of each motor. If the starting conditions require an equal variation of tractive effort on each step, together with the same upper limit of tractive effort on all steps except the first (on which a lower tractive effort is required), the variation of current during the



(*a*) (*b*)

FIG. 178.—Pertaining to Calculations of Starting Rheostats.

series portion of the starting period will be as shown in Fig. 178 (*b*). Denote the upper and lower limits of current by I_1 I_2, respectively, and the initial current (which is between I_1 and I_2) by I.

Then initially, $I = V/R_1$; where V denotes the line voltage which is assumed to be constant.

The resistance R_1 is kept in circuit until the current decreases to the lower limit, I_2, when the first section $(R_1 - R_2)$ is cut out so as to obtain the upper current limit I_1. The current change from I_2 to I_1 is assumed to take place instantaneously in all cases, i.e. the speed is unchanged.

Hence, since the counter-E.M.F. of any motor is proportional to the product of flux and speed, the counter-E.M.Fs. of each motor immediately prior and subsequent to the change in the circuit conditions are

$\frac{1}{2}(V - I_2R_1) = k\Phi_2$, and $\frac{1}{2}(V - I_1R_2) = k\Phi_1$, respectively.

Whence $\qquad (V - I_1R_2)/(V - I_2R_1) = \Phi_1/\Phi_2.$

Similarly, the resistance R_2 is kept in circuit until the current decreases again to its lower limit, I_2, when the second section $(R_2 - R_3)$ is cut out so as to obtain the upper limit, I_1. Hence, the counter-E.M.Fs. immediately prior and subsequent to this change are

$$\tfrac{1}{2}(V - I_2R_2) = k\Phi_2, \text{ and } \tfrac{1}{2}(V - I_1R_3) = k\Phi_1, \text{ respectively.}$$

Whence $\quad (V - I_1R_3)/(V - I_2R_2) = \Phi_1/\Phi_2.$

This process is continued until, finally, the last section $[(R_n - R_{n+1}) = (R_n - 2R_m)]$ is cut out. For this step we have

$$\tfrac{1}{2}(V - I_2R_n) = k\Phi_2, \text{ and } \tfrac{1}{2}(V - 2I_1R_m) = k\Phi_1.$$

Whence $\qquad (V - 2I_1R_m)/(V - I_2R_n) = \Phi_1/\Phi_2.$

Hence generally

$$\frac{\Phi_1}{\Phi_2} = \frac{V_1 - I_1R_2}{V - I_2R_1} = \frac{V - I_1R_3}{V - I_2R_2} = \ldots = \frac{V - 2I_1R_m}{V - I_2R_n} \quad . \quad (31)$$

These, then, are the fundamental equations connecting the circuit resistances of the steps for the specified starting conditions. Observe that the ratio of the fluxes is involved as well as the limits of current.

When the rheostats consist of only two or three sections the resistances of these sections may be determined by solving the general equations (31) by trial and error. Thus the upper limit of current, I_1, being fixed the flux Φ_1 is obtained from the magnetization curve (or, alternatively, from the speed curve if the magnetization curve is not available). The lower limit is then assumed, Φ_2 is obtained from the magnetization curve and R_2 is calculated, R_1 being known from the initial conditions. The value of R_2 is then substituted and a solution obtained for R_3, and so on, until finally the value obtained for R_m, when solving the final equation, should agree with the actual resistance of the motor, otherwise a fresh trial must be made with a different value for I_2.

Such a trial and error method, however, is not to be recommended on account of its tediousness and the amount of time consumed. The method is, of course, impracticable when the number of sections is large. Moreover, since the ultimate requirement is the resistances of the sections, rather than the circuit resistances of the successive steps, a method is desirable in which the former can be calculated directly. For these cases one of the simplest analytical solutions (which is universal in its application) is that developed by the author and given in a paper to the Institution of Electrical Engineers.*

Starting with the fundamental equations (31), the numerators are divided throughout by I_1 and the denominators by I_2, thus

$$\frac{\Phi_1/I_1}{\Phi_2/I_2} = \frac{V/I_1 - R_2}{V/I_2 - R_1} = \frac{V/I_1 - R_3}{V/I_2 - R_2} = \ldots = \frac{V/I_1 - 2R_m}{V/I_1 - R_n} \qquad \text{(i)}$$

Let $\qquad \lambda = (\Phi_1/I_1)/(\Phi_2/I_2)\,;\ \gamma = I_2/I_1\,;\ \zeta = I_1/I.$

Then $\quad V/I_1 = V/I\zeta = R_1/\zeta.$

$\qquad V/I_2 = V/I_1\gamma = R_1/\gamma\zeta.$

Substituting these values in equations (i), we have

$$\lambda = \frac{R_1/\zeta - R_2}{R_1/\gamma\zeta - R_1} = \frac{R_1/\zeta - R_3}{R_1/\gamma\zeta - R_2} = \ldots = \frac{R_1/\zeta - 2R_m}{R_1/\gamma\zeta - R_n} \quad . \qquad \text{(ii)}$$

Cross-multiplying, we have

$$R_1/\zeta - R_2 = \lambda(R_1/\gamma\zeta - R_1) = R_1\lambda(1/\gamma\zeta - 1) \qquad \text{(iii}a\text{)}$$

$$R_1/\zeta - R_3 = \lambda(R_1/\gamma\zeta - R_2) \quad . \quad . \qquad \text{(iii}b\text{)}$$

etc. $\qquad$ etc.

* "A universal 'Chart' method of calculating starting rheostats for direct-current motors." *Journal I.E.E.*, vol. 60, p. 867. An alternative method is given in vol. 58, p. 645. Paper by Dr. S. P. Smith on "Analytical determination of the steps in the starter of a series motor."

Add $(R_1 - R_1/\zeta)$ to each side of the first equation, so as to eliminate R_1/ζ from the left-hand side, and simplify, thus

$$R_1 - R_2 = R_1\left\{\frac{\lambda}{\gamma}\left(\frac{1}{\zeta} - \gamma\right) + \left(1 - \frac{1}{\zeta}\right)\right\} = KR_1 \quad . \quad . \quad . \quad \text{(iv}a\text{)}$$

Reduce the *left-hand* sides of equations (iii*b*), (iii*c*), etc., to the form $(R_2 - R_3)$, $(R_3 - R_4)$, etc., by subtracting successively the lower from the upper equation of each pair (i.e. subtract equation (iii*b*) from (iii*a*), equation (iii*c*) from (iii*b*), and so on). Thus

$$R_2 - R_3 = \lambda(R_1 - R_2) = \lambda KR_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(iv}b\text{)}$$

$$R_3 - R_4 = \lambda(R_2 - R_3) = \lambda^2 KR_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(iv}c\text{)}$$

$$R_n - 2R_m \doteq \lambda(R_{n+1} - R_n) = \lambda^{n-1}KR_1 \quad . \quad . \quad . \quad . \quad . \quad \text{(iv}_n\text{)}$$

Observe that these equations give directly the resistances of the sections of the rheostat, and that there is a common ratio (λ) between the resistances of successive sections. Observe, also, that the numerical value of λ depends upon the quotient of the ratio of fluxes and the ratio of currents corresponding to the current limits during starting (or alternatively upon the ratio of the tangents of the angles formed by lines drawn from the origin to the points on the magnetization curve corresponding to these currents). Thus the *value of λ depends upon the slope of that portion of the magnetization curve which lies between the current limits I_1, I_2.* Its maximum value is unity—which corresponds to a straight-line magnetization curve (i.e. a magnetic circuit worked at extremely low flux densities)—and its minimum value is equal to γ. In the latter case the flux is constant, and if the substitution $\lambda = \gamma$ be made in equations (iv) we obtain the resistances of the rheostat sections for a shunt motor.

Proceeding with the determination of a general relationship between λ and γ, we add together the whole of the left-hand sides of equations (iv*a*) to (iv*n*), inclusive, and perform a similar operation on the right-hand sides. The result is

$$\begin{aligned} R_1 - 2R_m &= KR_1\,(1 + \lambda + \lambda^2 + \ldots + \lambda^{n-1}) \\ &= KR_1\,(1 - \lambda^n)/(1 - \lambda) \\ &= R_1\left\{\frac{\lambda}{\gamma}\left(\frac{1}{\zeta} - \gamma\right) + \left(1 - \frac{1}{\zeta}\right)\right\}\frac{1 - \lambda^n}{1 - \lambda} \quad . \quad . \quad . \quad . \quad . \quad \text{(v)} \end{aligned}$$

Whence by rearrangement

$$\frac{2R_m}{R_1} = 1 - \left\{\frac{\lambda}{\gamma}\left(\frac{1}{\zeta} - \gamma\right) + \left(1 - \frac{1}{\zeta}\right)\right\}\frac{1 - \lambda^n}{1 - \lambda} \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(vi)}$$

But if e is the voltage drop in the *two* motors corresponding to the current I, then $e = 2R_mI$. Hence $2R_m/R_1 = (e/I)/(V/I) = e/V$.

The relationship between γ and λ can therefore be calculated for definite numbers of sections, and definite values of (e/V) and ζ $(= I_1/I)$. Moreover, the results can be plotted in the form of universal curves for general use. Such calculations have been made by the author for a number of starting conditions, and the curves are published in the *Journal of the Institution of Electrical Engineers*, vol. 60, pp. 870–880.

These curves give the *general* relationship between γ and λ/γ for values of n between 2 and 12, inclusive, for $\zeta = 1{\cdot}5$, and for appropriate values of (e/V). The relationship is given for γ and λ/γ, instead of for γ and λ, since $\lambda\,\gamma = \Phi_1/\Phi_2$, and therefore the co-ordinates represent the ratio of currents and the ratio of the corresponding fluxes, thereby enabling a second or

particular relationship between these quantities to be plotted on the appropriate curve sheet (or preferably a sheet of superimposed tracing paper). The point of intersection of this (second) curve with the appropriate curve on the chart, therefore, gives both γ and λ.

Traction operating conditions, however, render it desirable for the rheostat designer to have freedom in the selection of the initial starting current, so that in this case the ratio I_1/I cannot be fixed for the purpose of calculating the general relationship between λ and γ. But the above principle can be adapted to include this case. Thus, by re-arranging equation (vi) after substituting e/V for $2R_m/R_1$, we obtain

$$\frac{1}{\zeta}\left(\frac{\lambda}{\gamma}-1\right) = (1-e/V)\ \frac{1-\lambda}{1-\lambda^n} - (1-\lambda) \quad . \quad . \quad . \quad . \quad . \quad (\text{vi}a)$$

Therefore, the quantity $(\lambda/\gamma - 1)/\zeta\ [= (\Phi_1/\Phi_2 - 1)/(I_1/I)]$ can be calculated in terms of λ for given values of n and e/V. The results are plotted in the curves of Fig. 179 and give the *general* relationship between λ and $(\lambda/\gamma - 1)/\zeta$. The *particular* relationship between these quantities for the particular motor, starting conditions, and number of steps in the controller, is obtained as follows—

The upper limit of current I_1, is either given directly or is obtained from the current-tractive-effort curve of the motor for the specified upper limit of the tractive effort. Three values—say I_2', I_2'', I_2'''—are assumed for the lower limit of current over a range which should be a little greater than that actually expected during starting, but the range selected is immaterial, provided, of course, that all the assumed values are below the upper limit of current. The ratios of currents (i.e. I_2'/I_1, I_2''/I_1, I_2'''/I_1) are calculated.

The fluxes Φ_1, Φ_2', Φ_2'', Φ_2''', corresponding to these currents are obtained either directly from the magnetization curve or indirectly from the speed curve. Usually the latter procedure will have to be adopted. In this case, assuming that the given speed curve is that corresponding to the line voltage V, calculate the internal E.M.Fs. corresponding to the currents I_1, I_2', I_2'', I_2''' and a terminal voltage (per motor) V. Obtain the speeds s_1, s_2' s_2'', s''', and calculate the flux ratios. Thus, since flux is proportional to (counter-E.M.F./speed), we have

$$\frac{\Phi_1}{\Phi_2'} = \frac{s_2'(V - I_1R_m)}{s_1(V - I_2'R_m)};\quad \frac{\Phi_1}{\Phi_2''} = \frac{s_2''(V - I_1R_m)}{s_1(V - I_2''R_m)};\quad \frac{\Phi_1}{\Phi_2'''} = \frac{s_2'''(V - I_1R_m)}{s_2(V - I_2'''R_m)}$$

where R_m is the resistance of the motor circuit appropriate to the speed curve in use.

Next calculate λ corresponding to the above ratios of fluxes and currents (e.g. $\lambda' = (\Phi_1/I_1)/(\Phi_2'/I_2')$, etc.), and from the given initial starting current calculate the quantities $(\lambda'/\gamma' - 1/\zeta)$, etc. These calculations are quickly carried through if arranged in tabular form as in the example which follows. Plot the results on a slip of tracing paper superimposed upon Fig. 179, and determine the point of intersection with the appropriate curve. λ and γ are then determined.

Determination of number of steps for given starting conditions. When the initial starting current and the limits of currents during starting are fixed the number of steps in the starter for a given motor can be calculated by substituting appropriate values in equation (vi*a*) and solving for n. Thus

$$n = \log\left\{1 - \frac{(1-\lambda)(1-e/V)}{1-\lambda + (\lambda/\gamma - 1)/\zeta}\right\}/\log\lambda \quad . \quad . \quad . \quad . \quad (\text{vii})$$

A simpler process, however, is to determine which of the appropriate curves of Fig. 179 has co-ordinates corresponding to the given values of λ and

$(\lambda/\gamma - 1)/\zeta$. Thus values for the quantities λ and $(\lambda/\gamma - 1)/\zeta$ are calculated for the given starting conditions and the particular motor. Co-ordinates corresponding to these values are drawn in Fig. 179, and the appropriate e/V curve which pases through, or is nearest to, the point of intersection of the co-ordinates gives the value of n directly.

Example. Calculation of the sections of the starting rheostat for the series steps of a standard tramcar controller to be used with two 50-h.p., 525-volt motors the characteristics of which are given in Fig. 26. The resistance of each motor is 0·45 ohm. The initial tractive effort per motor at starting is to be 1100 lb. and the maximum tractive effort per motor is to be approximately 1700 lb.

To comply with the starting requirements we refer to Fig. 26 and select the initial starting current at 77A, and the upper limit of current at 105A. Hence $\zeta = I_1/I = 105/77 = 1{\cdot}36$. The voltage drop in the *two* motors at a current of 77A is $77 \times 2 \times 0{\cdot}45 = 69{\cdot}3$ V. Whence $e/V = 69{\cdot}3/525 = 0{\cdot}132$.

We next calculate the particular relationship between λ and λ/γ for a fixed upper limit of 105A and lower limits of 80A, 70A, 60A. The calculations are arranged in tabular form

I_1	105						
I_2			80		70		60
$\gamma(= I_2/I_1)$		0·762		0·666		0·571	
Voltage drop per motor	47·2		36		31·5		27
Internal E.M.F. per motor $(= E)$	477·8		489		493·5		498
Speed (from Fig. 26) $(= s)$	13·7		15·6		16·7		18·2
$\lambda/\gamma(= E_1s_2/E_2s_1)$*		1·112		1·18		1·275	
$(\lambda/\gamma - 1)/\zeta$		0·0822		0·132		0·202	
λ		0·848		0·787		0·728	

Plotting these results on Fig. 179 we obtain the point of intersection with the interpolated curve for $e/V = 0{\cdot}132$, $n = 3$, as $\lambda = 0{\cdot}78$, $(\lambda/\gamma - 1)/\zeta = 0{\cdot}142$. Whence $\lambda/\gamma = 1{\cdot}193$, $\gamma = 0{\cdot}654$, and $I_2 = 68{\cdot}6$A.

Now $R_1 = 525/77 = 6{\cdot}82$ ohms.

Hence substituting in equation (iv*a*) we have

$$R_1 - R_2 = R_1 \left\{ [\lambda(1/\zeta - \gamma)/\gamma] \div (1 - 1/\zeta) \right\} = 6{\cdot}82 \times 0{\cdot}362$$
$$= 2{\cdot}47 \text{ ohms.}$$

and from equations (iv *b*), etc.,

$$R_2 - R_3 = \lambda(R_1 - R_2) = 0{\cdot}78 \times 2{\cdot}47 = 1{\cdot}93 \text{ ohms.}$$
$$R_3 - R_4 = \lambda(R_2 - R_3) = 0{\cdot}78 \times 1{\cdot}93 = 1{\cdot}5 \text{ ohms.}$$

Calculation of resistances of sections for parallel steps.—These calculations are effected by an extension of the above method, the same fundamental principles being involved. We shall consider the case in which rheostats are connected in the circuit of each motor, as is necessary when transition is to be made by the bridge method (Fig. 111). The equations deduced for this case can be applied to cases where a single rheostat is employed—as with tramcar controllers—but the values of the resistances obtained from the application of the equations must be halved. If transition is effected at the current I_2 (per motor), and I_{1p} is the upper limit of current (per motor) for

* E_1, s_1 denote the internal E.M.F. and speed, respectively, at the current I_1; E_2, s_2 denote these quantities for the assumed lower current limits, I_2.

the parallel steps, then, assuming the speed to be unchanged during the transition period, we have for the transition step

$$\Phi_{1p}/\Phi_2 = (V - I_{1p}\, R_{1p})/(\tfrac{1}{2}V - I_2 R_m)$$

where R_{1p} is the resistance in circuit with each motor on the first parallel step. If the lower limit of current for the parallel steps is the same as that for the series steps,* and the resistances in circuit with each motor on the second and subsequent parallel steps are R_{2p}, R_{3p}, . . . R_n', n' being the number of sections, the general equations for the parallel steps are—

$$\frac{\Phi_{p1}}{\Phi_2} = \frac{V - I_{1p}R_{2p}}{V - I_2\, R_{1p}} = \frac{V - I_{1p}R_{3p}}{V - I_2\, R_2p} = \ldots = \frac{V - I_{1p}R_m}{V - I_2\, R_n'} \quad . \quad (32)$$

Whence

$$\frac{\Phi_{1p}/I_{1p}}{\Phi_2/I_2} = \frac{V/I_{1p} - R_{2p}}{V/I_2 - R_{1p}} = \ldots = \frac{V/I_{1p} - R_n}{\cdots\cdots} \quad . \quad . \quad . \quad (\text{viii})$$

Similarly for the transition step

$$\frac{\Phi_{1p}/I_{1p}}{\Phi_2/I_2} = \frac{V/I_{1p} - R_{1p}}{\tfrac{1}{2}V/I_2 - R_m} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (\text{ix})$$

Denoting $(\Phi_{1p}/I_{1p})/(\Phi_2/I_2)$ by λ_p; I_2/I_{1p} by γ_p; V/I_{1p} by R_1' $(= \gamma_p R_o)$; V/I_2 by $R_o(= R_1/\gamma\zeta)$; substituting in equations (viii) and (ix), and cross-multiplying we have

$$R_1' - R_{1p} = \lambda_p\,(\tfrac{1}{2}R_o - R_m) \quad . \quad . \quad . \quad . \quad . \quad . \quad (\text{x}a)$$

$$R_1' - R_{2p} = \lambda_p\,(R_o - R_{1p}) \quad . \quad . \quad . \quad . \quad . \quad . \quad (\text{x}b)$$

$$R_1' - R_{3p} = \lambda_p\,(R_o - R_{2p}) \quad . \quad . \quad . \quad . \quad . \quad . \quad (\text{x}c)$$

etc. etc.

From equation (x*a*) we obtain

$$R_{1p} = R_1' - \lambda_p\,(\tfrac{1}{2}R_o - R_m) = R_o\gamma_p - \lambda_p(\tfrac{1}{2}R_o - R_m) \quad . \quad . \quad (\text{xi}a)$$

and by successive subtraction of equations (x*a*), (x*b*), etc., we have

$$R_{1p} - R_{2p} = \lambda_p\,\{(R_o - R_{1p}) - (\tfrac{1}{2}R_o - R_m)\}$$

$$= \lambda_p\,(\tfrac{1}{2}R_o + R_m - R_{1p}) \quad . \quad . \quad . \quad . \quad . \quad . \quad (\text{xi}b)$$

$$R_{2p} - R_{3p} = \lambda_p\,(R_{1p} - R_{2p})$$

$$= \lambda_p^2\,(\tfrac{1}{2}\,R_o + R_m - R_{1p}) \quad . \quad . \quad . \quad . \quad . \quad . \quad (\text{xi}c)$$

etc. etc.

Whence

$$R_{1p} - R_m = (\tfrac{1}{2}\,R_o + R_m - R_{1p})\,(\lambda_p + \lambda_p^2 + \ldots \lambda_p^{n'})$$

$$= (\tfrac{1}{2}R_o + R_m - R_{1p})\,\lambda_p\,(1 - \lambda_p^{n'})/(1 - \lambda_p) \quad . \quad . \quad (\text{xii})$$

Substituting for R_{1p} from equation (xi*a*), and denoting $\lambda_p(1 - \lambda_p^{n'})/(1 - \lambda_p)$ by a, we have, after re-arranging and simplifying equation xii,

$$\frac{R_m}{R_o} = \frac{(1 + a)\,(\gamma_p - \tfrac{1}{2}\lambda_p) - \tfrac{1}{2}a}{(1 + a)\,(1 - \lambda_p)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (\text{xiii})$$

* This condition corresponds to the majority of cases of automatic control equipments for motor-coach trains. The method can be readily adapted to cover the cases in which the lower limits of current differ.

Now $R_m/R_o = (e/I)/(V/I_2) = (e/V)\,(I_2/I)$, where e is the voltage drop per motor corresponding to the current I.

Hence

$$\frac{e}{V}\cdot\frac{I_2}{I}=\frac{(1+a)\,(\gamma_p-\frac{1}{2}\lambda_p)-\frac{1}{2}a}{(1+a)\,(1-\lambda_p)} \qquad \text{(xiv)}$$

Hence the general relationship between λ_p and γ_p can be calculated for various numbers of sections and for appropriate values of the product (e/V) (I_2/I). A set of curves can then be plotted to give the general relationship between λ_p/γ_p and γ_p. Such a set of curves is given in Fig. 179A*.

The curve giving the particular relationship between λ_p/γ_p and γ_p is obtained in the same manner as for the series steps, but in the present case the lower limit of current I_2 is fixed, and therefore values are assumed for the upper limit.

Starting rheostats for locomotives. The problems connected with the design of rheostats for locomotive service involve the consideration of a number of special features. Thus a locomotive may be required to haul trains of various weights, and also to run light.

Again, when starting a heavy train up a gradient, the tractive-effort required may approach the limiting value at which slipping of the driving wheels occurs. Under these conditions it is imperative that the limiting tractive-effort be not exceeded on any notch, and the controller must be held on a notch until the current has decreased to the minimum value. The rheostats should therefore be proportioned to allow of considerable time being spent on each notch. Thus with control equipments for heavy freight locomotives it is standard practice to install rheostats having a 5-minute rating, while under exceptionally severe operating conditions continuously-rated rheostats are installed. These equipments form a striking contrast to those for motor-coach trains, in which a 20-second rating for the rheostats is general practice.

Moreover, in starting a long loose-coupled freight train the initial tractive effort must be limited to a low value, and must be increased in small increments to pull the slack gradually out of the couplings. In this case it is very important that the variation of tractive effort during starting shall not exceed a definite value.

The starting and accelerating operations are, therefore, effected with the aid of an ammeter connected in the circuit of one motor, as the driver then has an indication of the extent of the variation of the tractive effort on the several steps.

On account of the variable conditions of operation, transition cannot always be effected at the same current, and, in consequence, full advantage cannot be taken of the bridge method. Hence, for series-parallel control, shunt transition is usually employed, and, to avoid a sudden restoration of normal tractive-effort when the motors are first connected in parallel, one or two extra resistance notches must be provided in the parallel-transition positions of the controller.

The calculation of the resistances of the rheostat sections is, therefore, not so simple as in the cases previously considered. The problem is difficult and complicated; it is probably best tackled by arranging the grading of the rheostats to give uniform variations of tractive effort, together with the same upper limit of tractive effort on each step, when starting the normal

* Tabulated values of a are given in the Author's paper (*Journ. I.E.E.*, v. 60, p. 871).

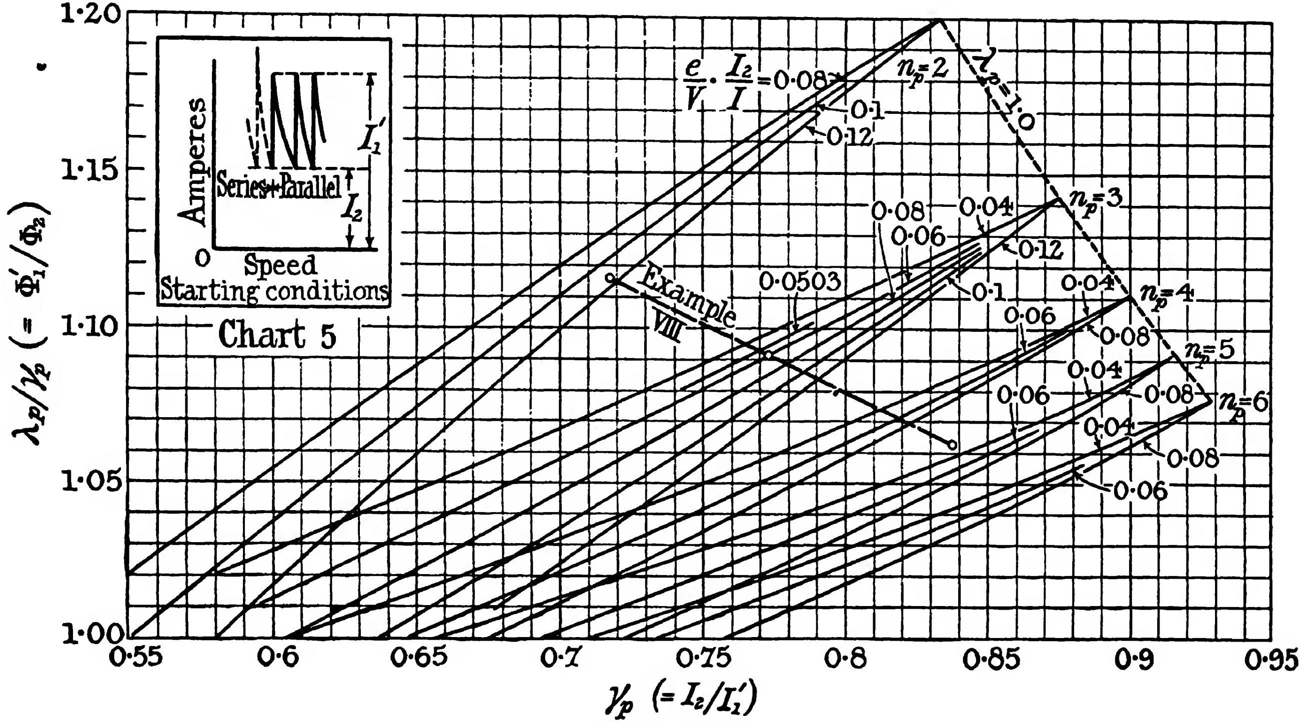


FIG. 179A.—Chart for Calculation of Sections of Starting Rheostat (Parallel Combination of Motors).

or average load. Additional steps are then arranged to meet the special starting conditions.

In these circumstances the current-speed curve will not follow the regular "saw tooth" shape (Fig. 178) during the early portions of the starting period even when the normal load is being started, and irregularities will occur with other loads. But if both the variation and the maximum value of the tractive effort are within the prescribed limits the starting performance may be

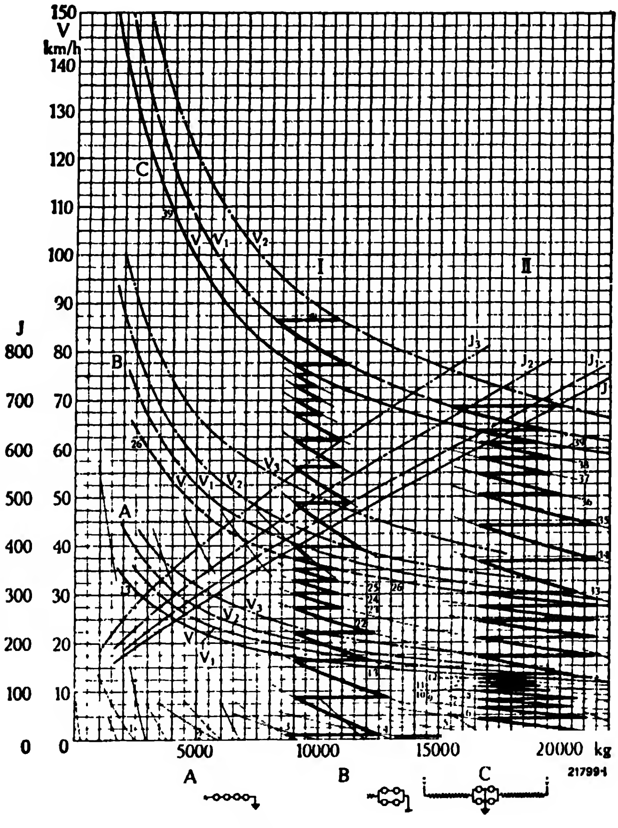


FIG. 180.—Variation of Tractive-effort of Locomotive during Starting Heavy and Moderately-heavy Loads.

[NOTE.—The locomotive is equipped with four motors, of which the characteristics are given in Fig. 37, and is controlled according to the scheme shown in Fig. 176. The speed curves V, V_1, V_2, V_3 correspond, in order, to 100%, 78%, 61%, 43% field excitation. The numbers, 1 39, against the tractive-effort/speed curves indicate the positions of the master controller.]

considered as satisfactory. The calculations* for the resistances of the additional sections are best effected by a graphical trial and error method.*

In Fig. 180 are given the speed/tractive-effort and current/tractive-effort curves for a 4000-h.p. 1500-volt, locomotive equipped with four motors of the type illustrated in Fig. 34 and controlled on the double series-parallel system according to the scheme shown in Fig. 176. The heavy "saw-tooth"

* A number of graphical methods, together with worked examples, are given in Chapter VIII of *Electric Motors and Control Systems*.

lines show the starting performances when the locomotive is starting heavy and moderately-heavy loads. In the former case all the combinations of the motors are employed. The initial tractive effort is 14,000 kg. (13·77 tons) the mean tractive effort is approximately 18,500 kg., and the variation of tractive effort during the initial steps is 4000 kg. With the moderately-heavy load only the series-parallel and parallel combinations are employed. The initial tractive effort is 9000 kg., the mean tractive effort is approximately 10,000 kg., and the variation of tractive effort during the initial steps is about 4000 kg. In both cases the tapped-field steps are used only in the parallel combination of the motors.

CHAPTER X

THE CONTROL OF SINGLE-PHASE RAILWAY MOTORS

THE control of the speed and torque of single-phase series railway motors is effected by variation of the applied voltage.* Since the operating voltage of the motors is much lower than the line voltage, a transformer forms an essential part of the equipment, and therefore the various voltages required for starting and speed control may be obtained from tappings on this transformer. Hence not only are rheostats dispensed with, but *each control point becomes a running point*, so that a number of economical speeds are available.

The **regulation of the voltage** may be effected in a number of ways, but those employed in modern equipments comprise (1) a group of contactors, (2) a tapping switch.

In all cases precautions must be taken when changing the voltage to avoid the successive short-circuiting of the different sections of the transformer winding. The method commonly employed is to connect a centre-tapped choking coil (called a "**preventive coil**") in the circuit between two adjacent contactors. This coil consists of a laminated magnetic circuit wound with a single winding which is tapped at the centre point. It offers a high impedance to a current passing through the winding from end to end, but exerts practically no choking effect upon current passing between the centre point of the winding and the two ends, as in this case the resultant ampere-turns are zero. When the winding is connected between adjacent tappings of the transformer the potential of the centre point is approximately midway between that of the tappings.

Contactor method of tap changing. The connections are shown diagrammatically in Fig. 181. The contactors (1, 2, . . . 6) are arranged in two groups (viz. 1, 3, 5; 2, 4, 6), with the common terminals of each group connected to a preventive coil, the centre-point of which is connected to the motor. Two contactors, normally connected to adjacent tappings, are closed on each notch. Each contactor, therefore, carries approximately one half of the motor current. Transition from one voltage to the next is effected by opening one contactor and closing another belonging to the same group.

Division of current in preventive coil. It will be of interest to investigate the currents in the two portions of the preventive coil and the motor voltage during transition.

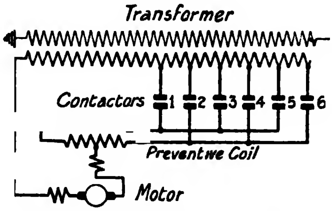
Under normal conditions the currents in the coil and the sections of the transformer are distributed in the manner shown in Fig. 182 (*a*), the vector difference between the currents in the two portions of the coil being equal to twice the normal magnetizing current. Fig. 182 (*b*) shows the vector diagram for these conditions. The vectors OE_1, OE_2 represent the voltages of the tappings to which the coil is connected: the vectors OI, OI_0 represent the

* In a few isolated and exceptional cases the control is effected by brush shifting. See *The Engineer*, vol. 113, p. 522; vol. 114, p. 11.

motor current and the normal magnetizing current of the coil respectively. The currents in the two portions of the coil are therefore represented by OI_1 and OI_2.

The motor voltage is obtained by subtracting vectorially the voltage drop in the right-hand portion of the coil from OE_1. Oa represents the induced voltage in this portion of the coil, Ob the internal voltage drop due to resistance, and Oc—the resultant of Oa and Ob—the total internal voltage drop. The motor voltage is given by OV, the resultant of OE_1 and Oc.

When one-half of the coil carries the motor current the whole of the ampere-turns are expended in the magnetic circuit, and a considerable



Sequence of Contactors

Notch	Contactors 1	2	3	4	5	6
1	●	●				
2		●	●			
3			●	●		
4				●	●	
5					●	●

FIG. 181.—Connections for Contactor Method of Tap Changing.

choking effect will be produced unless the magnetic circuit is designed with a high reluctance.

The vector diagram for this case is shown in Fig. 183 (*b*), in which OI represents the motor current, Oa the induced voltage, Ob the internal voltage

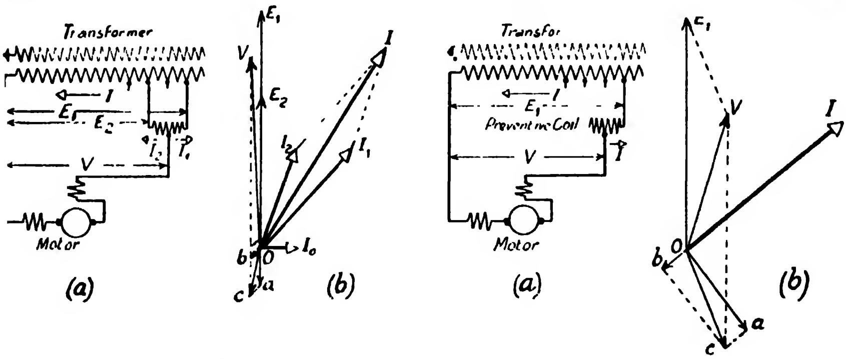
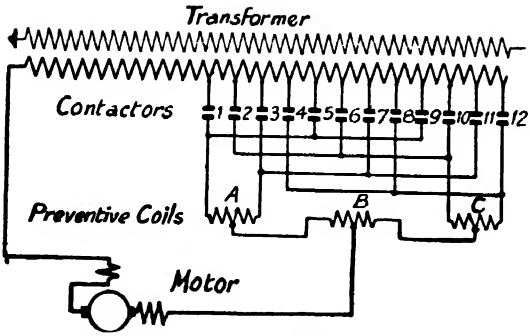


FIG. 182. FIG. 183.
Vector Diagrams showing the effect of Preventive Coil on Motor Voltage.

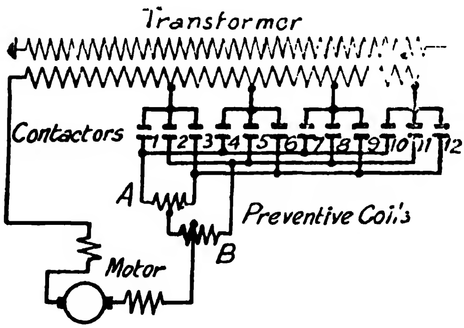
drop due to resistance, and Oc the total internal voltage in the half-coil which is carrying the current. Hence the motor voltage is given by OV.

Contactor methods of tap changing for large currents. Owing to certain difficulties in the design of alternating-current contactors for large currents (above 1000 amperes) it is now the practice, when contactors are to be employed for tap changing, to divide the current between a number of contactors. A simple method is shown in Fig. 184 and is an extension of that shown in Fig. 181. Three preventive coils are employed, and the motor current divides between four contactors. These connections, however, require the use of a large number of contactors and a large number of tappings on the transformer.

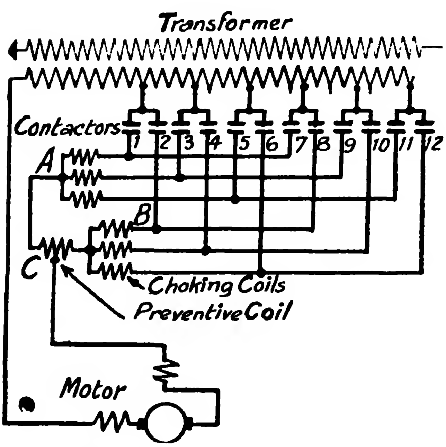


Step	Contactors 1	2	3	4	5	6	7	8	9	10	11	12
1	●	●	●	●								
2		●	●	●	●							
3			●	●	●	●						
4				●	●	●	●					
5					●	●	●	●				
6						●	●	●	●			
7							●	●	●	●		
8								●	●	●	●	
9									●	●	●	●

FIG. 184.—Contactor Method of Tap Changing for Large Currents. (Westinghouse.)



Step	Contactors 1	2	3	4	5	6	7	8	9	10	11	12
1	●	●	●									
2		●	●	●								
3			●	●	●							
4				●	●	●						
5					●	●	●					
6						●	●	●				
7							●	●	●			
8								●	●	●		
9									●	●	●	
10										●	●	●



Step	Contactors 1	2	3	4	5	6	7	8	9	10	11	12
1	●	●	●	●	●	●						
2		●	●	●	●	●	●					
3			●	●	●	●	●	●				
4				●	●	●	●	●	●			
5					●	●	●	●	●	●		
6						●	●	●	●	●	●	
7							●	●	●	●	●	●

FIGS. 185, 186.—Alternative Contactor Methods of Tap-changing for Large Currents. (Allmanna Svenska Elektriska A.B. and Siemens-Schuckert).

Figs. 185, 186 show alternative methods which possess the advantage that fewer tappings are required on the transformer. In the method shown in Fig. 185 the current divides between three contactors. Two preventive coils are employed; one (A) is tapped at its mid-point, and the other (B) is tapped at one-third of its winding, as the current in the portion having the smaller number of turns is normally twice that in the

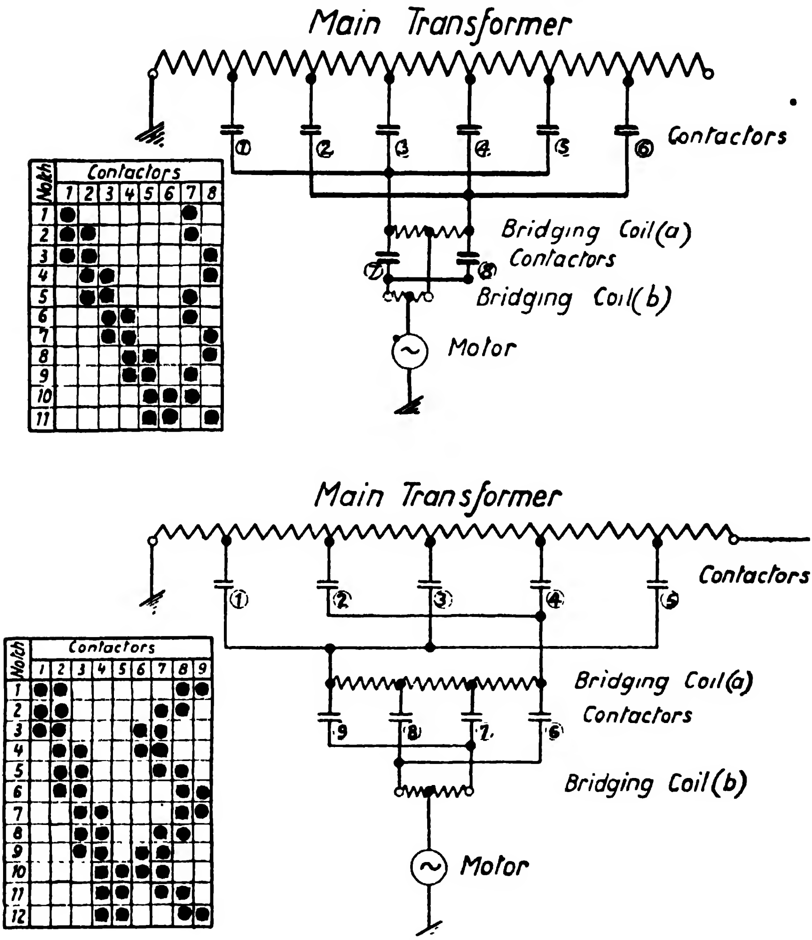


FIG. 187.—Contactor Methods of Obtaining a Number of Operating Voltages with Few Tappings on Transformer. (Oerlikon.)

other portion of the coil. The coil A is connected to two of the contactors of each group (e.g. 1, 2,; 4, 5; 7, 8; etc.), and the other coil, B, is connected to the third contactor of each group and to the mid-point of A. By closing the contactors in the order shown in Fig. 185, three operating voltages are obtained from each pair of tappings on the transformer. For example, on the first step contactors 1, 2, 3 are closed and the preventive coils are connected to the first tapping. On the second step

contactors 2, 3, 4 are closed and coil A is connected across the first and second tappings, coil B remaining connected to the first tapping. On the third step coil B is transferred to the second tapping, and on the fourth step the other end of coil A is transferred to the second tapping. Hence, if n voltages are available from the transformer, $3(n-1)+1$

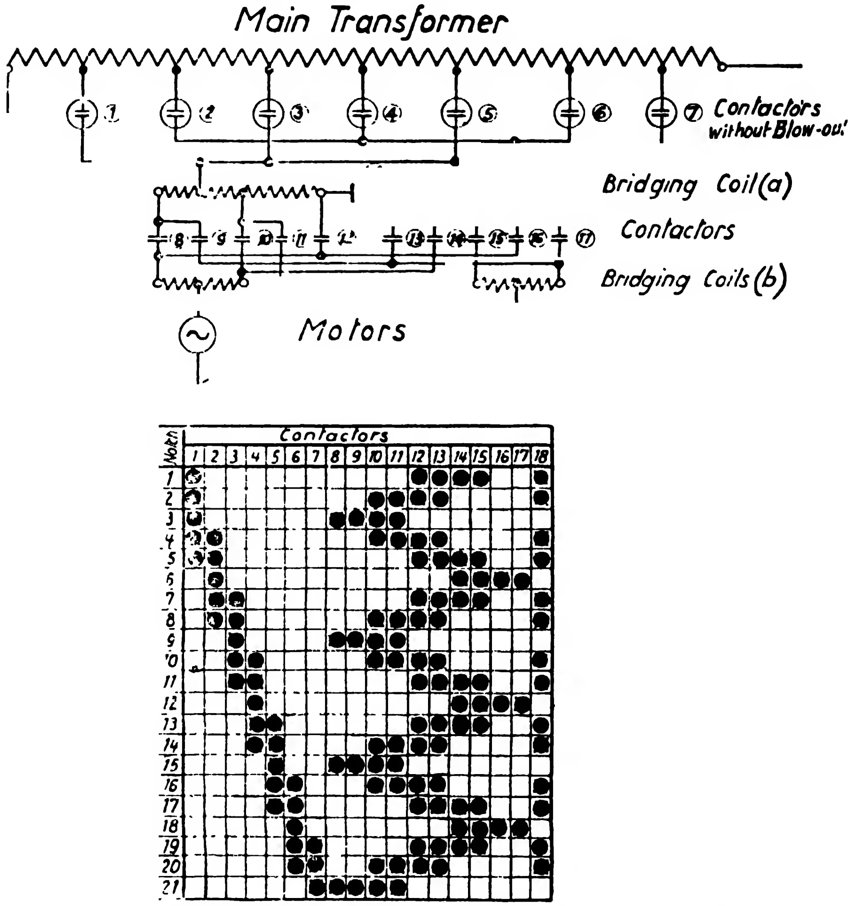


FIG. 187A.—Contactor Method of Obtaining a Large Number of Operating Voltages with Few Tappings on Transformer. (Oerlikon.)

operating voltages are available for the motor with the use of $3n$ contactors.

In the method shown in Fig. 186 the motor current divides between six contactors. One preventive coil, C, and two three-limbed choking coils, A, B, are required. The contactors are closed in the order shown in Fig. 186, and two operating (motor) voltages are available from each tapping beyond the third.

Contactor methods of obtaining a number of voltages with few tappings on transformer. One method, shown in Fig. 185, has been referred to in

the preceding section. Other methods are shown in Figs. 187, 187A.* In the two methods shown in Fig. 187 two bridging coils *a*, *b* are employed, of which one (*a*) is used as an auto-transformer and the other (*b*) as a preventive coil. In one case the auto-transformer is centre-tapped, and in the other case it has two tappings. The combinations obtained by using these auto-transformers in conjunction with the preventive coil (*b*) and the tappings on the transformer are shown in the sequence charts.

An extension of these methods is shown in Fig. 187A, which refers to a two-motor equipment or its equivalent. With a single motor equipment one of the bridging (preventive) coils, *b*, and the corresponding group of four contactors (e.g. Nos. 8, 10, 14, 16 *or* 9, 11, 15, 17) would be eliminated. The bridging coils (*b*) function both as auto-transformers and choking coils, and the tappings on the main transformer are used both singly and in pairs. For example, tapping No. 1 is in use on notches 1, 2, 3;

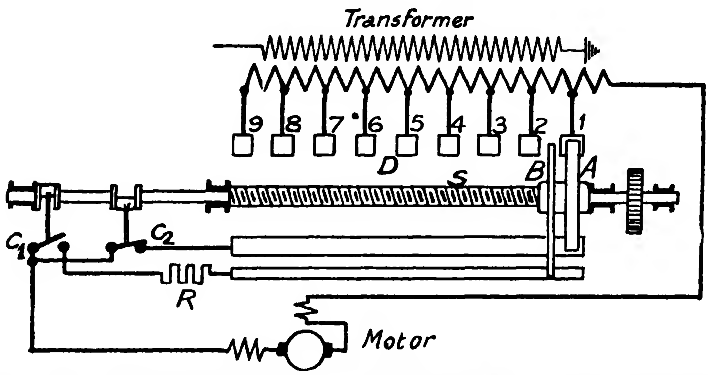


FIG. 188.—Tapping-switch Method of Tap-changing. (Brown-Boveri.)

Nos. 1 and 2 on notches 4, 5: No. 2 alone on notch 6; Nos. 2 and 3 on notches 7, 8; etc. Transition from one tapping to the next is effected in conjunction with contactor No. 18, which is connected between the bridging coils (*a*). Any arcing occurring during this process is taken on this contactor, and, in consequence, arc-rupturing devices are unnecessary on the contactors (Nos. 1–7) connected to the tappings of the main transformer.

Tap changing by double-contact sliding switch. The double-contact type of switch which is employed for voltage regulation in direct-current accumulator installations is also suitable for tap changing. For this purpose the switch is arranged with its contacts in a straight line and the moving elements are fixed to a carriage which is operated by either a screw- or a chain-driven mechanism. Sparking or arcing at the sliding contacts is prevented by two contactors which are mechanically operated in synchronism with the sliding contacts and are so connected that all circuits are made and broken at the contactors.

Fig. 188 shows the connections for the simplest case. The sliding contacts *A*, *B* are insulated from each other and are fitted to a carriage

* The methods shown in Figs. 187, 187A, represent the latest Oerlikon practice; the connections of Fig. 187 being employed for motor-coaches, and those of Fig. 187A for locomotives.

which is operated by the screw S, the pitch being equal to that of the fixed contact blocks, D, which are connected to the tappings of the transformer. The contactors C_1, C_2 are operated by cranks fitted to an extension of the screw S. One contactor, C_1, is connected to a preventive resistance, R, and the other contactor, C_2, short circuits this resistance, together with the contacts of contactor C_1. When either of the sliding contacts A, B is fully on one of the fixed contacts, contactor C_2 is closed and C_1 is open. When both of the sliding contacts are on adjacent fixed contacts (i.e. during transition), both contactors are closed, and the preventive resistance is connected between the sliding contacts.

The cycle of operations in changing from one tapping to the next is as follows—

Assuming the switch to be in the position shown in Fig. 188 and contactor C_2 to be closed, the forward rotation of the screw causes B to

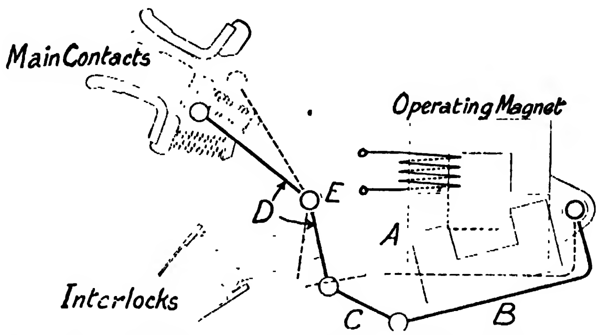


FIG. 189.—Magnet and Lever System of Siemens-Schuckert Electromagnetic Contactor. (Full lines show Contactor in open position, dotted lines show Contactor closed.)
A, armature; B, lever fixed to armature; C, link; D, bell-crank lever pivoted at E.

make contact with block 2. Contactor C_1 is then closed and contactor C_2 is opened before A leaves contact block 1. Contactor C_1 remains closed while switch B is passing across block 2. Contactor C_2 closes immediately after A makes contact with block 2, and C_1 opens just before B leaves this block.

CONTROL APPARATUS

Contactors. These are usually of the electromagnetic type in European equipments, although in some cases electro-pneumatic contactors are employed. Electro-pneumatic contactors are adopted universally with American equipments.

The **electro-pneumatic contactor** for alternating-current circuits closely resembles, and in some cases is almost identical with, its prototype for direct-current circuits. It possesses a number of advantages over the electromagnetic type. Thus (1) the higher contact pressure enables a smaller width of contact to be employed for a given current, thereby resulting in a lighter moving contact and a lower eddy-current loss in the contacts; (2) the operating mechanism is simpler and lighter than that of an electromagnetic contactor; (3) the energy required for operation and control is very small.

The electromagnetic valves are usually identical with those for direct-current equipment and are supplied with direct current at a low voltage.

The **electromagnetic contactor** for alternating-current circuits differs in a number of features from a similar contactor for direct current circuits. In general, the former is much heavier than the latter and requires more energy for its operation. Moreover, a number of difficulties are encountered in its design which are non-existent in the direct-current contactor. For example, (1) to obtain rapid action the moving contact must be operated through a system of levers from a relatively light moving armature ; (2) the magnetic circuit must be laminated ; (3) chat-

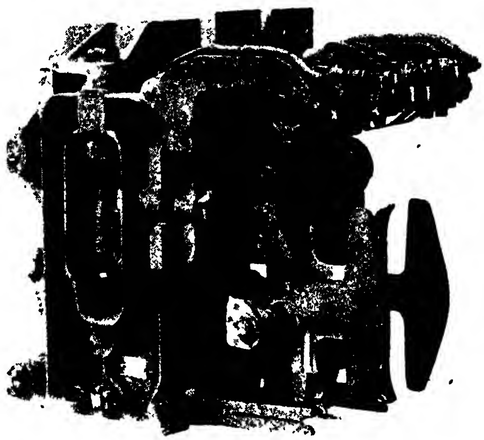


FIG. 190.—Siemens-Schuckert Electromagnetic Contactor with Arc Chute Removed.

tering or vibration of the moving armature due to the alternating flux must be prevented ; (4) the main contacts must be laminated or divided to reduce eddy currents (which would be generated in solid contacts by the alternations of the blow-out field) ; (5) the current in the operating coil varies with the position of the moving armature and the ratio of maximum to minimum current—corresponding to the open and closed positions, respectively—may be of the order of 5 to 1.

A sketch of a typical magnet and lever system is given in Fig. 189, and a typical contactor is illustrated in Fig. 190. The design is such that the load on the armature of the magnet (due to the weight of the moving parts) increases as the air gap decreases, but becomes very small when the air gap approaches zero. Chattering is prevented by short-circuited coils (called " shielding coils ") of copper in each of the pole faces, each coil embracing approximately one-half of a pole face. The circulating currents due to the alternating flux cause a phase difference between the fluxes in the two portions of the pole faces, with the result that the variation of the resultant flux is relatively small and a practically steady pull is obtained.*

* The theory of the " shielded-pole " electromagnet is given in the Author's *Theory and Practice of Alternating Currents*, p. 384.

The contact pressure is obtained by a compound compression spring, which is designed to give a high pressure both initially and finally. Rapid opening is thereby ensured.

The strong blow-out field is confined, by pole-pieces of special design,

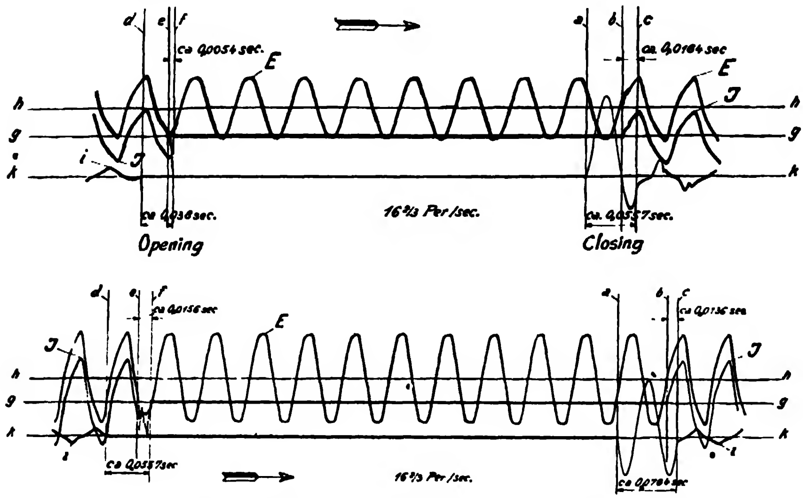


FIG. 191.—Reproduction of Oscillograms showing Operation of Siemens-Schuckert Electromagnetic Contactor on 16⅔-cycle System.

Upper oscillogram.—Contactor breaking 1294 amp. (r.m.s.), *J*, at 76·3 volts, *E*. *Lower oscillogram*—Contactor breaking 2560 amp. (r.m.s.), *J*, at 125 volts, *E*: *a*, operating coil energized at 170 volts, 16⅔ cycles; *b*, main contacts touch; *c*, armature (of magnet) closes; *d*, voltage removed from operating coil; *e*, main contacts open; *f*, arc ruptured; *g*, zero line, main current; *h*, zero line, voltage; *i*, current in operating coil; *k*, zero line, operating-coil current.

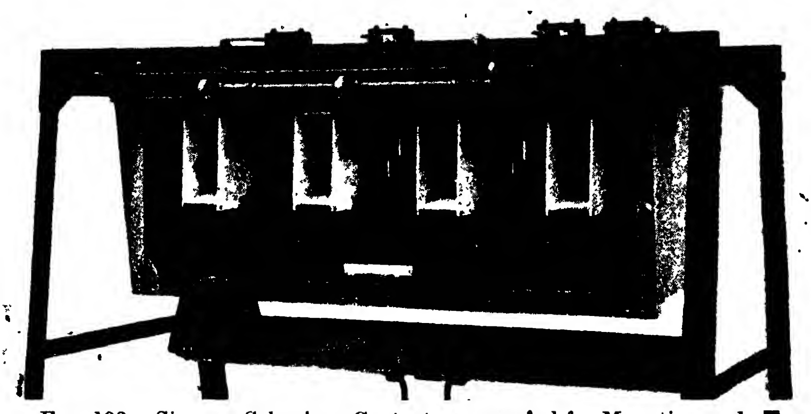


FIG. 192.—Siemens-Schuckert Contactors arranged for Mounting under Motor-coach.

to the space occupied by the contact tips and arcing horns, and a sharp rupture of the arc is obtained. This feature is shown in the reproduced oscillograms shown in Fig. 191. These oscillograms show also the variation of current in the operating coil during the closing of the contactor.

Fig. 192 shows a group of contactors arranged for under-frame

mounting. The divided main contacts, the interlocks, and the copper strip connections between the contactors are shown clearly.

Typical electro-pneumatic contactors are shown in Fig. 193, this illustration referring to a group of Oerlikon contactors installed in the

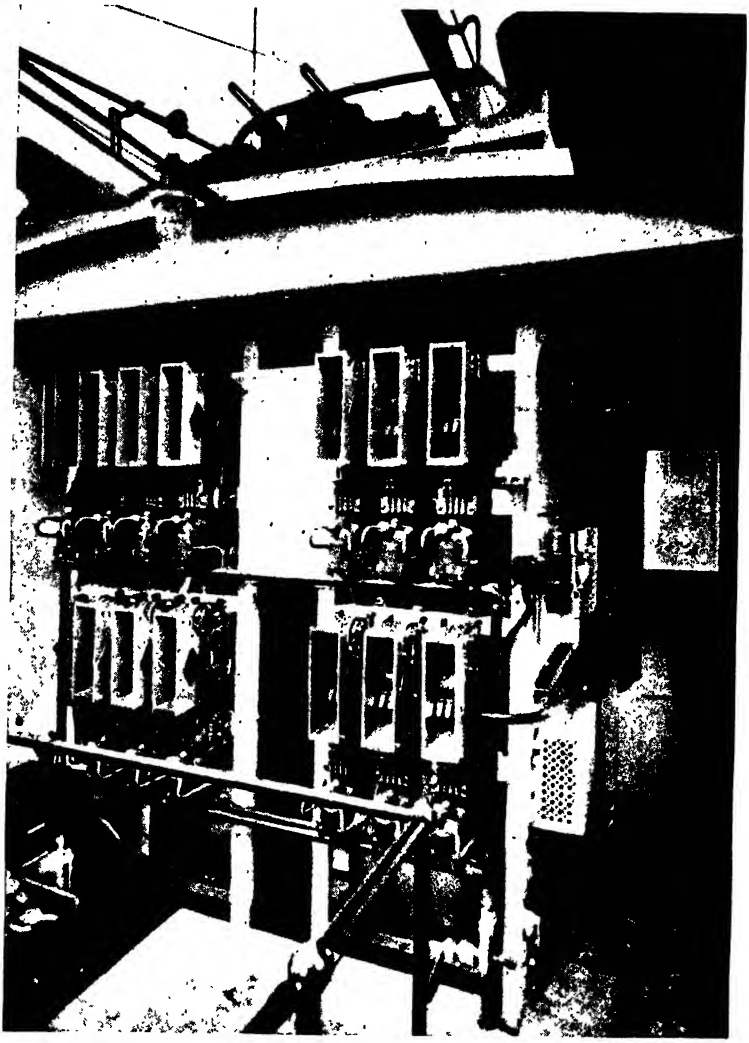


FIG. 193.—Oerlikon Electro-pneumatic Contactors Installed in Motor-coach.

control department of a motor-coach (described in Chap. XVI). The driving equipment of the coach consists of a single frame-mounted motor rated at 518 h.p., 490 volts.

Fig. 194 illustrates the latest form of Oerlikon cam-operated contactors, or step switches, for heavy currents. The switches are of the

double-throw type with the contacts arranged vertically; the fixed contacts being mounted upon twin mica-insulated steel rods fitted to a frame built up of steel plates and sections. The moving contacts are fitted to the ends of a number of double levers, which are arranged in two groups; the levers of each group being pivoted to horizontal shafts and operated by geared camshafts which are driven by a small motor. Provision is also made for hand operation in emergencies. The switching

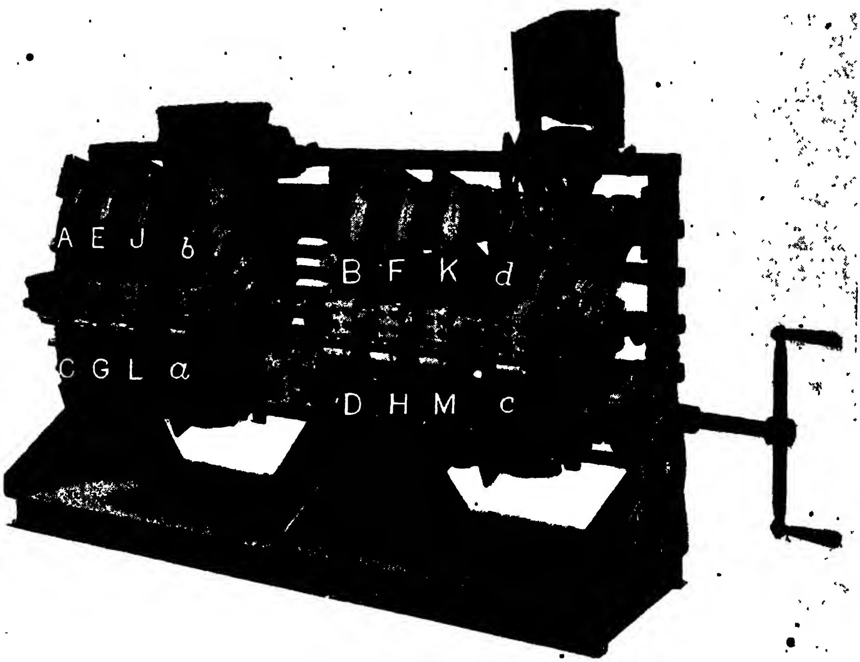


Fig. 194.—Oerlikon Cam-operated Step Switches for Locomotive Service.

operations are so arranged that all arcing is confined to one switch of each group, the contacts of which are provided with a magnetic blow-out.

The switch group shown in Fig. 194 is arranged for controlling the motors according to the scheme of Fig. 181, nine tappings being required on the transformer. The tappings are connected to the fixed contacts in the following manner—

Tappings No. 1 to switches *A* and *B*; No. 2 to switches *C* and *D*; No. 3 to switch *E*; Nos. 4 to 9 taken in order to switches *F* to *M* taken in order. The preventive coil is connected to the fixed contacts of switches *a* and *c*, these contacts being also connected to the blow-out contacts of *b* and *d*.

With the exception of the first two steps, the switching from tapping to tapping is carried out in the same order as in the contactor group of Fig. 181, but in the present case the circuits are always made and broken by the switches *b*, *d*, which are fitted with magnetic blow-out. Thus, assuming tappings 2 and 3 to be in use, switches *D*, *E*, *a*, *b*, *c*, *d* will be

closed. NOTE.—Switches *a*, *c* short-circuit the blow-out contacts *b*, *d* respectively, and are in series with *D* and *E*, respectively.) The forward rotation of the camshafts to the next step causes the following cycle of operations to take place : (i) switch *c* opens ; (ii) *d* opens ; (iii) *D* opens ; (iv) *F* closes ; (v) *d* closes ; (vi) *c* closes.

The corresponding circuit changes are* : (i) the short-circuit across the blow-out contacts *d* is removed ; (ii) the circuit via tapping 2 and preventive coil is opened at *d* ; (iii) tapping 2 is disconnected from the switch levers ; (iv) tapping 4 is connected to the switch levers ; (v) the

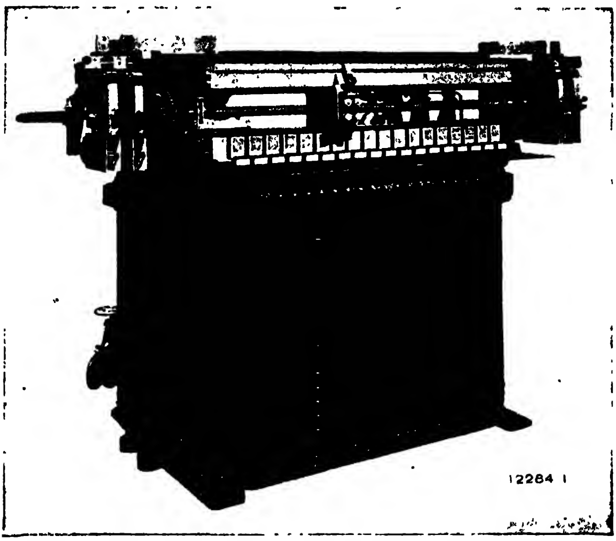


FIG. 195.—Brown-Boveri Tapping Switch Mounted on Transformer. (Two-motor Equipment.)

circuit via tapping 4 and preventive coil is established by the blow-out contacts *d* ; (vi) these contacts are short-circuited.

Similar cycles occur at each succeeding step, the left-hand and right-hand groups of switches acting alternately.

Tapping switches. The sliding-contact switch tap changer has been standardized by Messrs. Brown-Boveri for motor-coach and locomotive equipments, and nearly 300 of these switches are in service. A typical switch, mounted in position on the transformer, is illustrated in Fig. 195, from which the extreme compactness of this method of tap changing will be observed. The method of operation has already been considered in detail on p. 271.

The screw shaft operating the switch is chain driven by a small direct-current motor, and the arcing switches, or contactors, are actuated

* These circuit changes are identical with those which were effected, in earlier Oerlikon locomotive equipments, by means of a drum-type controller and two pairs of contactors operated through gearing from the controller drum. (See *Electric Motors and Control Systems*, pp. 308–310.)

by cranks fitted to this shaft. A slip-coupling is interposed between the motor and the driving chain-wheel.

The sliding contacts are usually of the laminated-brush type, but in some cases solid contacts are employed. With the laminated contact the laminations are set obliquely to the direction of motion so as to prevent

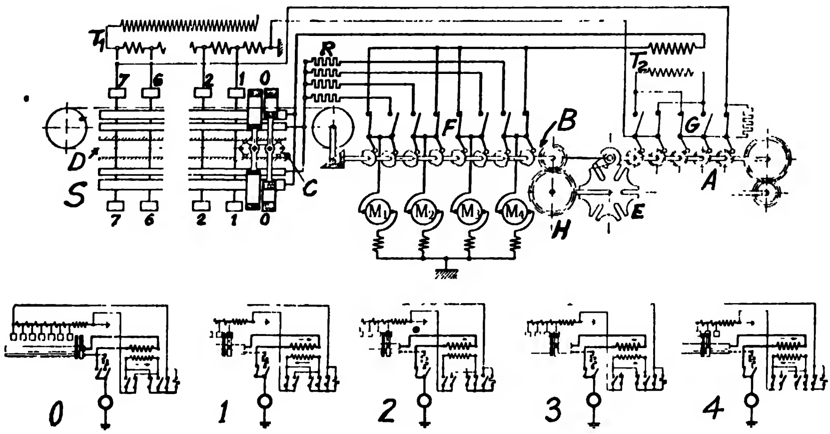


FIG. 196.

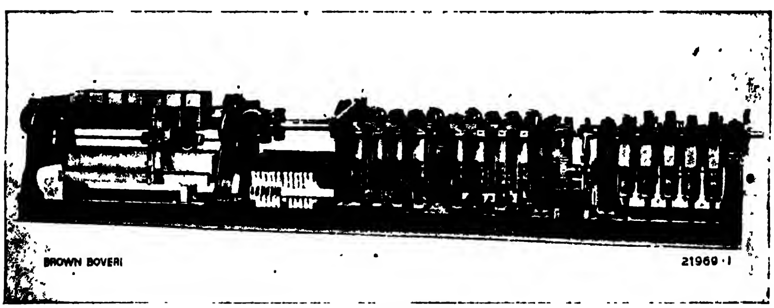


FIG. 197.

Brown-Boveri Tapping Switch and Circuit Diagrams for Four-motor Equipment. (The small diagrams show the circuit connections, for one motor, for the "off" position, and the first four notches of the master controller.)

the formation of grooves in the fixed contact bars and blocks. The sliding surfaces are lubricated automatically by felt pads.

Switches of the type illustrated in Fig. 195 are made with a maximum number of 18 switch positions, as although the switch itself could be arranged with a larger number of positions, difficulties are encountered in providing a larger number of tappings on the transformer. Accordingly, for the largest locomotives (for which 18 switch positions are insufficient) a special circuit has been developed by means of which a large number of switch positions is obtained with relatively few tappings on the

transformer. This circuit involves the use of an auxiliary, or booster, transformer, the primary winding of which is excited at constant voltage and the secondary winding is connected in series, successively, with the tappings of the transformer. Three operating voltages are, therefore, available from each tapping, viz. (1) the actual voltage of the tapping, (2), (3) the difference and sum of the voltages of the tapping and auxiliary transformer.

Figs. 196, 197 show the tapping switch and circuits for a four-motor equipment.

The sliding contacts of the tapping switch proper, *S*, are mounted on a carriage, *C*, and operated by an endless chain, *D*; this construction

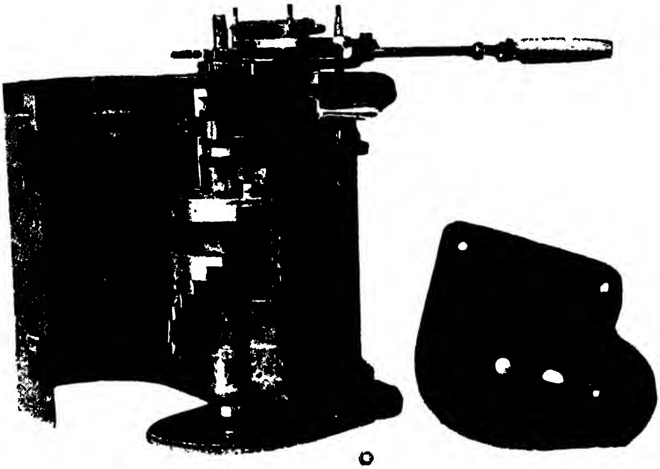


Fig. 198.—Westinghouse Master Controller with Cap-plate Removed. (Non-automatic Control.)

being both cheaper and less bulky than that having a screw spindle and travelling nut. The chain is driven through bevel gearing from the camshaft, *B*, which is geared to another cam-shaft, *A*, the latter being geared to the driving motor. The arcing switches, *F* (which consist of eight—two for each motor—cam-operated contactors, each having a magnetic blow-out and arc chute), are actuated by the cam-shaft, *B*, and correspond to the contactors C_1, C_2 in Fig. 188. The four preventive resistances (viz. one for each pair of arcing switches) are shown at *R*, and are located between the tapping switch and the arcing switches. The second group, *G*, of cam-operated contactors control the switching of the primary winding of the booster transformer, T_2, and effect the following combinations: (1) primary winding excited so that the secondary voltage opposes the voltage of main transformer, T_1; (2) primary winding short-circuited; (3) primary winding excited so that the secondary voltage assists the voltage of T_1. These operations have to take place at each position of the tapping switch proper, and the correct timing of the operations is effected by a special toothed gear, *E*, and the gearing *H*.

Reversers. These switches have to perform the same functions as

the reversing switches in direct-current equipments. Usually a throw-over drum-type switch is employed and is operated either electrically (by electromagnets) or electro-pneumatically.

Master controllers. Illustrations of typical master controllers for locomotive service are given in Figs. 198, 199. The controller of Fig. 198 is designed for controlling electro-pneumatic contactors according to the scheme shown in Fig. 184, the full connections being given in Fig. 206. The control circuit is supplied with direct current at low voltage.

The controller of Fig. 199 is designed for controlling a tapping switch (Fig. 197) and electro-pneumatic reversers. It possesses a number of special features which are described later (p. 286).

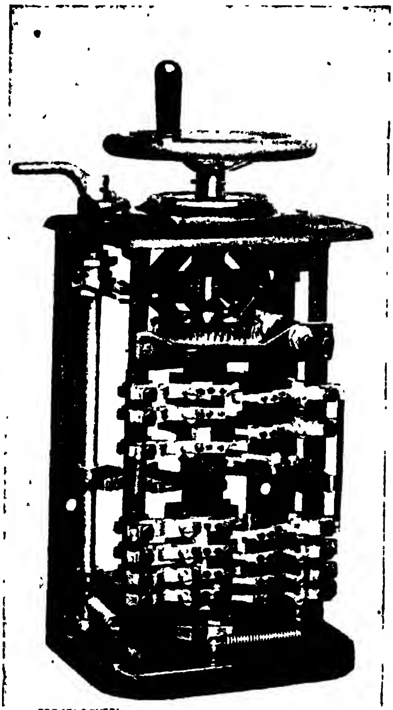


FIG. 199.—Brown-Boveri Master Controller.

Transformers. A single transformer is now employed for supplying the motors and the auxiliary circuits. The transformer is usually of the single-winding (auto-transformer) type, as this type possesses two advantages over the double-winding type : (1) a slight saving in active materials (about 3 per cent for the ratios of transformation common to single-phase traction circuits); (2) an unrestricted choice in the selection of the voltages for auxiliary, heating, and lighting circuits (these voltages may be chosen either equal to or higher than any of the motor operating voltages, the higher voltages being obtained by tappings on the primary portion of the winding). The single-winding transformer, however, necessitates the earthing of one side of the motor circuit.

The transformers may be either air cooled or oil cooled. Air cooling, by means of a blower, may be employed with a shell-type transformer and results in a considerable saving in weight compared with an oil-cooled transformer of the same output. The reduction in weight is due to the elimination of both the oil (the weight of which may be between 1000 and 2000 lb. for a transformer suitable for a locomotive) and the relatively heavy containing-tank.

The air-cooled (air-blast) transformer is practically standard with American equipments, and has been adopted in some European equipments. But the oil-cooled transformer is installed in the majority of European locomotive equipments, and is also standard for European motor-coach equipments. The chief reason for the preference of the oil-cooled transformer is that the oil-immersed windings are protected

against moisture and dust. Moreover, with oil cooling the possibility of "hot spots" (i.e. local high temperatures) is less than with air cooling.

With the large size (1000 to 2000 kVA.) of transformer necessary for a heavy locomotive and the restricted space available, it is not possible to provide sufficient cooling surface in the tank for the natural cooling of the oil. An external oil cooler and a circulating oil pump is, therefore, necessary. The external oil cooler takes the form of a series of tubes (through which the heated oil from the transformer is circulated) which are cooled by a current of air. The air blast is usually supplied by a motor-driven blower, but in a number of large express locomotives in service on the Swiss Federal Railways the tubes are mounted beneath the running board on one side of the locomotive and are cooled by air currents due to the motion of the locomotive. This method (which is due to Messrs. Brown-Boveri) has given very satisfactory results in practice.

Figs. 200, 201 illustrate a transformer, of about 2500 kVA., for locomotive service; transformers of this type being installed in the large Oerlikon goods locomotives (see Chap. XVII) in service on the Swiss Federal Railways.

The transformer is of the shell type and is oil immersed, the oil being cooled in an external cooler by an air blast. The blower and the oil pump (for circulating the oil through transformer and cooler) are motor driven.

The primary winding (which is designed for 15,000 volts, $16\frac{2}{3}$ cycles) has tappings to give 1000, 800, and 220 volts; the higher-voltage tappings being for train heating, and the low-voltage tapping for the auxiliary circuits on the locomotive. Two secondary windings are provided, each of which has nine tappings. The external connections from the tappings are arranged in the manner shown in Fig. 200 to facilitate connection to the step switches, which are of the type shown in Fig. 194.

An example of an oil-cooled transformer (built by Messrs. Siemens-Schuckert) of moderate output, with natural cooling, is illustrated in Fig. 202, and constructional details are shown in the drawings on Plate I. The transformer is of the shell type and has a single winding, which has ten tappings for the motor circuit and three tappings for the train heating circuits, as shown in the connection diagram on Plate I. Only one of the tappings for the heating circuits is in use at a time, and the object of providing three tappings is to enable different degrees of heat to be obtained.

The tank (which also contains the preventive coil) is of boiler plate, and its sides are fitted with radiator tubes. An outer casing (which is open at the top and bottom) is fitted around the tubes so as to increase the natural draught and the cooling effect. The oil is circulated through the ventilating ducts in the transformer windings and the radiator tubes by a motor-driven pump which is built into the tank. Thermometers (both direct and remote indicating) are fitted so as to give at all times an indication of the temperature of the oil.

Protective apparatus. The transformers and motors are protected against overload by means of automatic overload oil switches and fuses. High-frequency lightning discharges are prevented from reaching the transformer by means of some form of lightning arrester and choke coil.

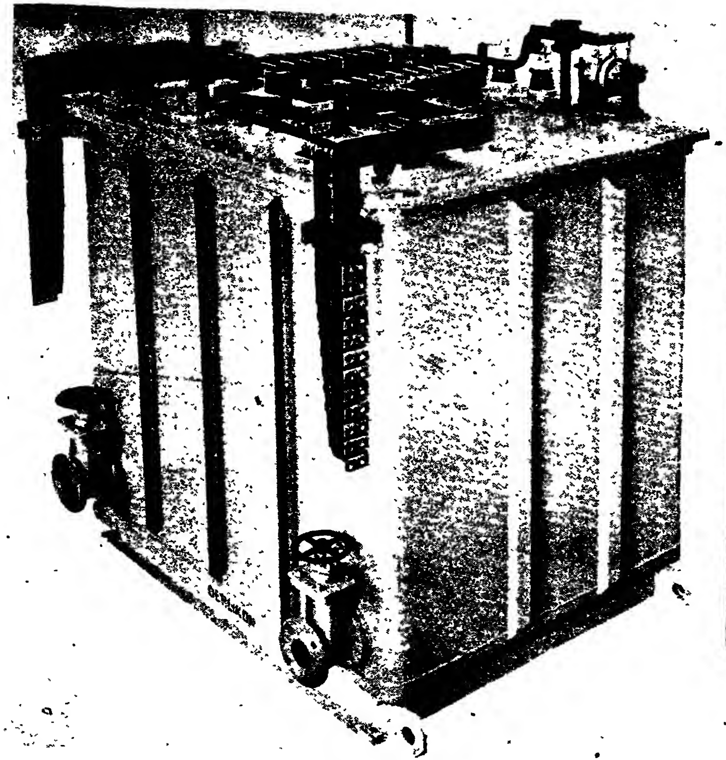


FIG. 200.

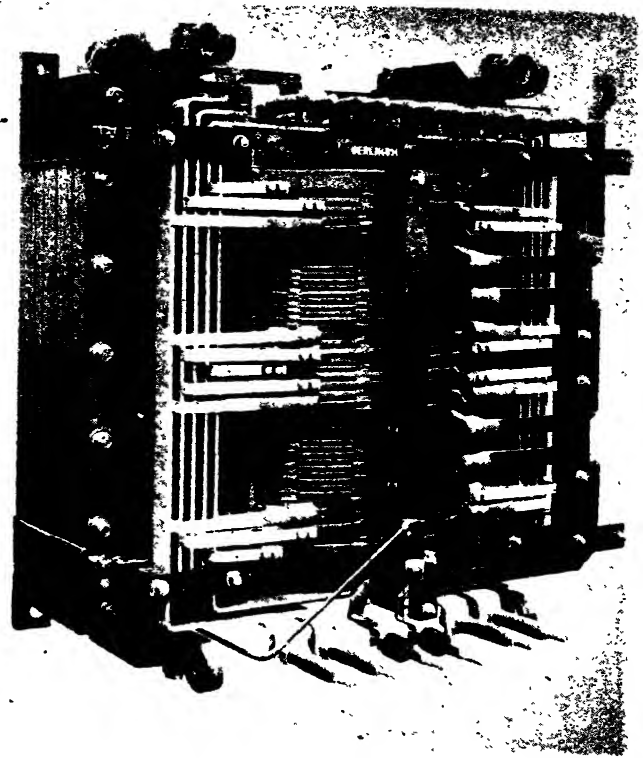


FIG. 201.

Oerlikon Oil-immersed Transformer for Locomotive Service.

NOTE.—The normal position of the core is horizontal and not vertical as shown in Fig. 201.

In some cases, where a single transformer supplies the motors and all the auxiliary circuits, a circuit breaker is inserted in the motor circuit in order that an overload on the motors shall not trip out the high-tension oil switch and so cut off the lighting and control circuits. The oil switches may be closed manually, electrically, or pneumatically.

It is not the practice to interrupt the primary circuit of the main transformer when power is cut off from the motors, as this procedure

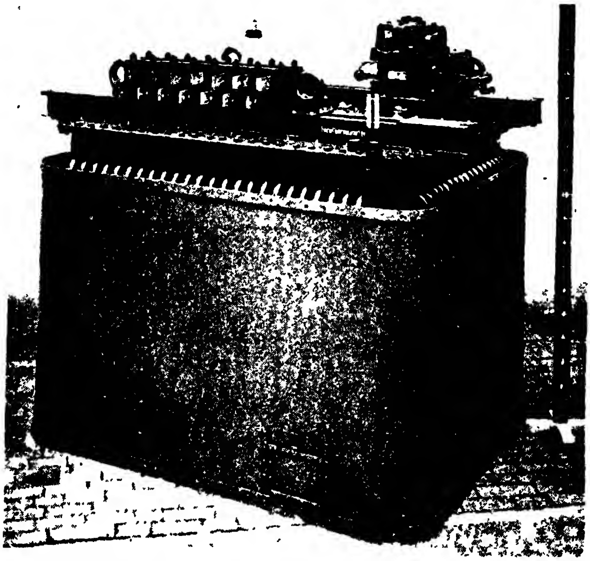


FIG. 202.—Siemens-Schuckert Oil-immersed Self-cooled Transformer.

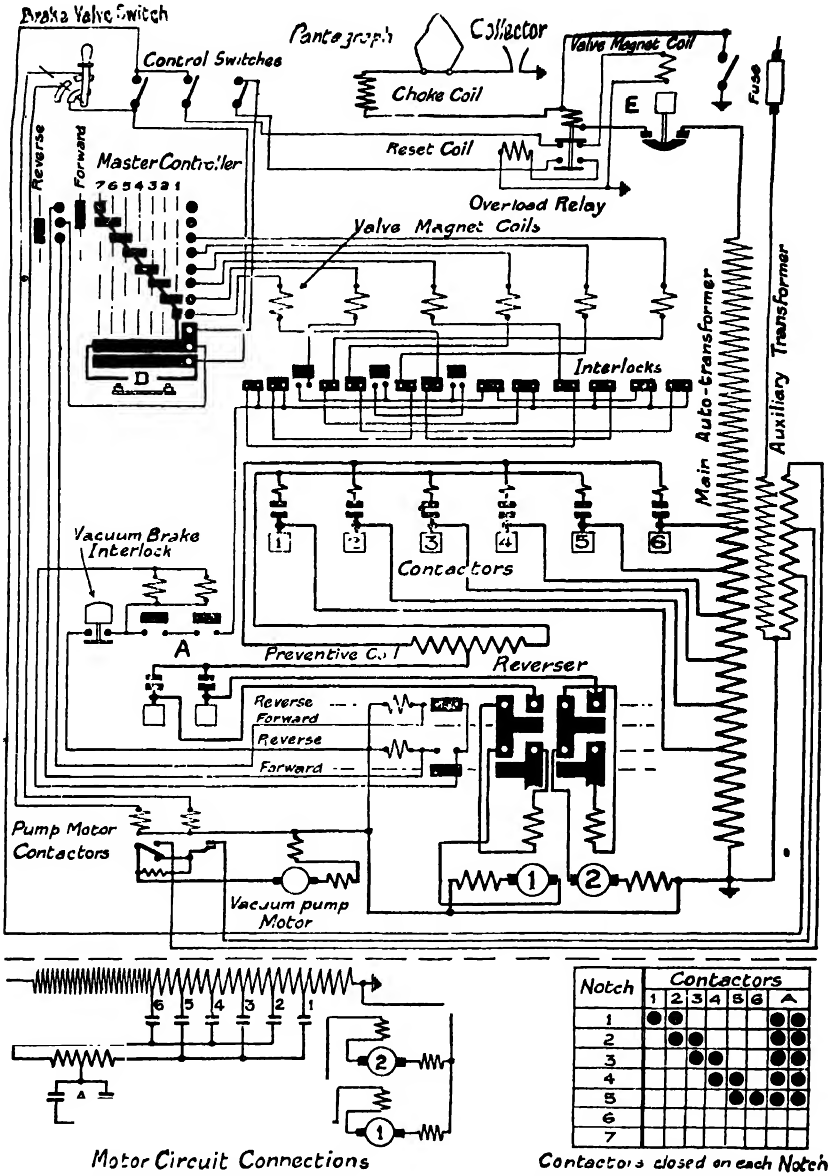
is liable to set up surges which may produce breakdowns in the insulation of the transformer and high-tension wiring.*

The oil switches, current and potential transformers, and all high-tension protective devices must be located in a steel "high-tension" compartment. The doors of this compartment must be mechanically interlocked with the current collectors, so that the doors cannot be opened when the collectors are in contact with the overhead line. The opening of the doors usually earths the high-tension circuit, and in some cases the current collectors cannot be raised when the doors are open. (See Chapters XVI and XVII for further details.)

EXAMPLES OF TYPICAL CONTROL SYSTEMS

Motor-coach multiple-unit control system. An example of the contactor system applied to a motor-coach, and arranged for multiple-unit control, is shown in Fig. 203. This example refers to the Westinghouse equipment in service on the Morecambe-Heysham single-phase experimental line of the London, Midland and Scottish Railway.

* In this connection see *Minutes of Proceedings of the Institution of Civil Engineers*, vol. 179, p. 92, paper on "The Electrification of the Morecambe and Heysham branch lines of the Midland Railway," by Messrs. J. Dalziel and J. Sayers.



Notch	Contactors 1	2	3	4	5	6	A	
1	●	●					●	●
2		●	●				●	●
3			●	●			●	●
4				●	●		●	●
5					●	●	●	●
6								
7								

FIG. 203.—Connections of Motor and Control Circuits for Westinghouse Single-phase Series Motors.

A special feature is that the master controller and control circuit are arranged to permit train operation with "mixed" equipments, e.g. electro-pneumatic control with electric interlocking, and "all-electric" control with mechanical interlocking.*

* Further details are given in *The Electrician*, vol. 61, pp. 324, 363, 371.

The main transformer is of the oil-cooled "auto" type, and is provided with six tappings. An auxiliary transformer supplies the control and auxiliary circuits at 150 volts. The control is electro-pneumatic, the "switch group" consisting of six contactors. The centre point of the preventive coil is connected to the motors through two additional contactors, *A** (called "line switches"), which are controlled from the reversing cylinder of the master controller. These contactors are electrically interlocked with those of the "switch group," so that the latter cannot be operated until the line switches are closed. Auxiliary contacts are also provided on the "switch group" for interlocking these contactors against incorrect operation.

The reverser is of the throw-over drum type, and is electro-pneumatically operated.

The master controller is arranged on the "dead man's handle" principle, and is provided with separate handles for reversing and speed control. When *either* the forward or the downward pressure on the main handle is released, the control circuit is interrupted at the bridging contacts *D* on the main cylinder.

The main automatic oil-switch *E* is electro-pneumatically operated. When the switch opens on overload, it can only be reset by returning the driving handle of the master controller to the "off" position.

The brakes are of the vacuum type, and the vacuum pump motor has two operating speeds, the higher speed being employed when a vacuum has to be created rapidly to release the brakes. The control is effected by a switch connected with the brake valve.

Control system for a large locomotive. This example refers to one of the recent 115-ton, 2800-h.p. (continuous) express passenger locomotives (equipped by Messrs. Brown-Boveri) in service on the Swiss Federal Railways. The four motors are supplied from a single auto-transformer having seven main tappings and giving no-load voltages (at 15,000 volts primary) of 104, 178, 237, 297, 357, 431, 505. The auxiliary machines are supplied from the 237-volt tapping and the train-heating circuits are supplied at either 800 volts or 1000 volts from two additional tappings.

Speed control is effected by a tapping switch (Fig. 196) in conjunction with a 118 kVA. booster transformer, the primary of which is excited at 505 volts and the secondary (20 volts) winding is connected in the main motor circuit so as to buck or boost the voltage of the main transformer according to the principle discussed on p. 278.

The tapping switch is driven (through chain gearing and a slip-coupling) by a direct-current series motor, which receives its supply—via the master controller—from the 36-volt train lighting circuit, this voltage (36 volts) being the standard voltage for train lighting on the Swiss Federal Railways.

The circuit diagram for the motors, tapping switch, and electro-pneumatic reversers is shown in Fig. 204. The circuits of the maste controller—in so far as they concern the tapping-switch motor—are

* These contactors were inserted to provide a break between the motor circuits, and to prevent the motors building-up as direct-current generators if the coach were hauled by a locomotive, with the reverser in the incorrect position.

shown in Fig. 205. This diagram shows also the mechanical arrangement of the controller, which has a number of special features, such as a "follow-up" device for stopping the tapping-switch motor, an indicator which shows the position of the tapping switch, and means for operating the tapping switch by hand in case of emergency. Formerly the control of the tapping-switch motor was effected by a "position regulator" or interlocking drum on the switch itself. The present arrangement results in a considerable simplification of the control circuit and at the same time gives the driver a clear indication of the position of the tapping switch.

The tapping-switch motor has two field windings (viz., one for each direction of rotation) and drives the transmission gearing through a slip-coupling. The tapping switch is locked in the operating positions by an electromagnetic pawl, which also controls the switch for starting and stopping the motor. Hence the control of the tapping-switch motor involves two switching operations, viz., connecting the appropriate field winding in circuit and closing and opening the circuit of the solenoid of the pawl. These operations are effected by two sets of fingers and segments in the master controller.

The **master controller**, Figs. 199, 205, is of the drum type; it has a driving hand-wheel mounted on a central spindle (A, Fig. 205) and an auxiliary, or reversing, handle and spindle B, which is interlocked with the former. The segments are arranged concentrically with the central spindle, but only the segment H is fixed thereto, the other segments being fitted to insulated drums which are mounted loosely either on this spindle or on a hollow shaft D. For example, the drum G is mounted loosely on the spindle A, and is operated through toothed segments by the reversing handle; the drum F is mounted loosely on the hollow shaft, and is operated through linkwork K, by the cam-lever L, which, in turn, is actuated by the roller-lever M fixed to the hollow shaft; the drum E is also loose on the hollow shaft and is actuated by the striker plate N fixed to drum F. The hollow shaft is connected to the spindle A by the bevel pinions of the differential gear C. This gear is fitted with a pointer P and a worm wheel and worm, the latter being coupled mechanically (by chain gearing) to the shaft of the tapping switch.

The **method of operation** is as follows: The reversing handle is set to the desired position, which operation energizes the appropriate valve magnet of the pneumatic cylinders of the reversers and connects the control supply to the fingers supplying the contact drums E, F. The hand-wheel is moved in the clockwise direction to the desired operating position, which causes the roller-lever, M, first to engage the cam-lever, L, and thereby actuate the contact drums, and then to move through an angle equal to that through which the hand-wheel was moved. Hence the solenoid Q of the pawl of the tapping switch locking device is energized and the tapping-switch motor starts.

The worm-wheel of the differential gear, being driven by the tapping switch, causes the hollow shaft to move backwards towards its initial position, owing to the operating spindle A being held stationary by a star-wheel and pawl. This causes the roller lever M finally to re-engage with the cam-lever L, and so return the contact drum F to its initial ("off") position, thereby interrupting the circuit of the solenoid of the

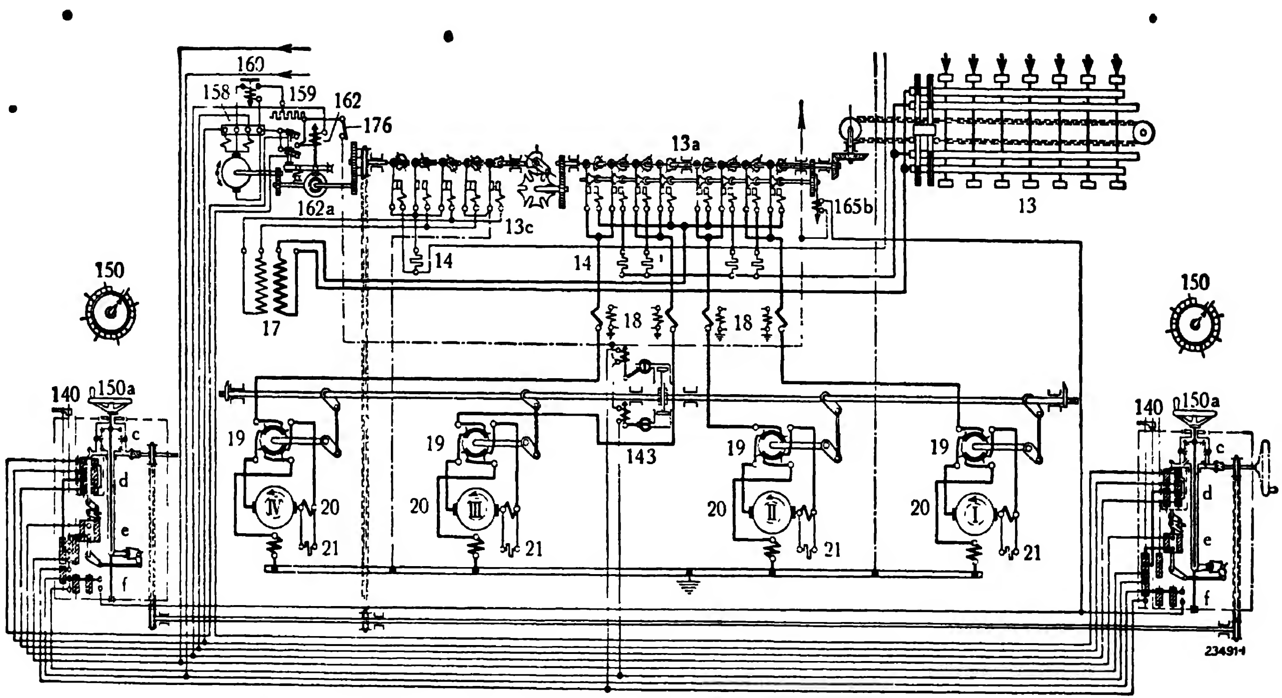


FIG. 204.—Connections of Brown-Boveri Control Apparatus for Four-motor Locomotive.

Reference.—13, tapping switch; 14, preventive resistances; 17, booster transformer; 18, current transformers; 19, reversers with electro-pneumatic operating gear (143); 20, 21, traction motors; 140, reversing handle; 150, tapping-switch position indicator (on master controller); 150*a*, master controller; 158, tapping-switch motor; 165*b*, quick-acting tripping device for tapping-switch contactors; 159–176 control apparatus for tapping-switch motor.

pawl Q. The circuit of the tapping-switch motor is opened when the pawl engages the slot in the locking wheel. The tapping switch is, therefore, brought to rest and locked, and any over-running of the motor is taken care of by the slip-coupling. The striker plate N however does not move the contact drum E during the return movement of M.

If the hand-wheel is moved farther in the clockwise direction to another position, the roller-lever engages the cam-lever and re-establishes the supply to the solenoid Q, which re-starts the tapping-switch motor. This circuit is again interrupted, as before, when the tapping switch reaches the position corresponding to the setting of the driving hand-wheel.

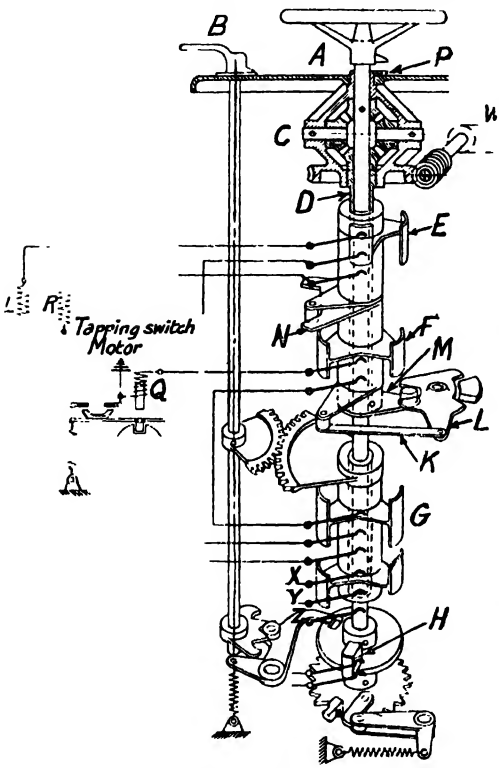


Fig. 205.—Arrangement of Circuits of Brown-Boveri Master Controller for Control of Tapping Switch.

(Note.—Fingers X, Y, Z control the electro-pneumatic reversers.)

If the hand-wheel is moved to a lower position (i.e. in the counter-clockwise direction) the drums E, F are thrown to their alternative positions and the tapping-switch motor is reversed. If, however, the hand-wheel is returned quickly to a position beyond the normal zero, or "off," position, a tripping device is energized (by means of the contacts H) which opens the arcing switches and disconnects the motors from the transformer.

The four **reversers** are mounted on their respective motors and are coupled to a longitudinal shaft, which is operated by differential air cylinders in the usual manner. Provision is made for hand operation (both of the reversers and the tapping switch) and for cutting out, if necessary, any of the motors.

When the tapping switch is returned to its zero, or "off," position the cam-operated arcing switches (F, Fig. 197) are all opened, so that the motors are entirely disconnected from one another; they cannot, therefore, build up as direct-current generators in the event of the locomotive being hauled with the reversers in the incorrect position.

In order quickly to cut off power from the motors in an emergency, the cam-operated arcing switches are fitted with an electromagnetic tripping device which causes these switches to open instantaneously. The tripping device is energized—by means of contacts H (Fig. 205)

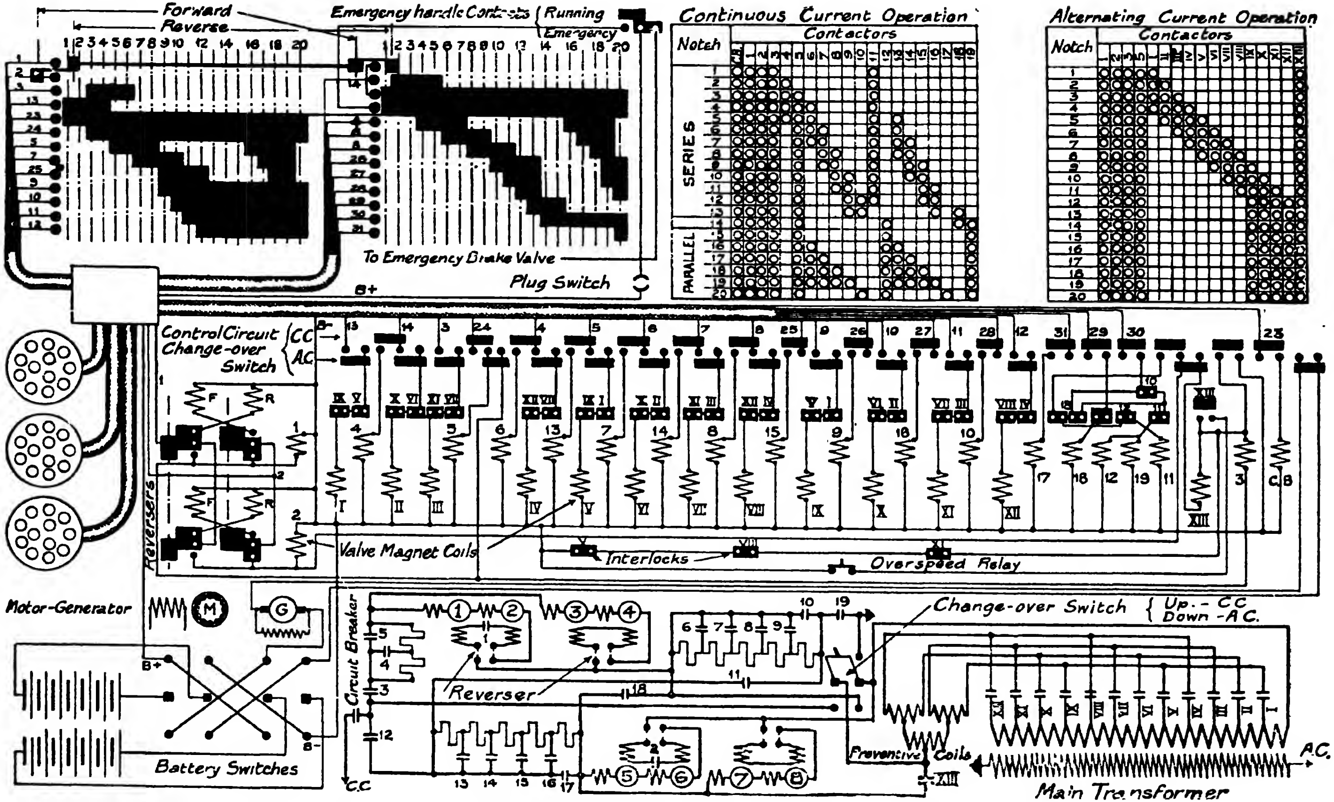


FIG. 206.—Motor and Control Circuit Connections for Combined Alternating-current and Direct-current Operation (Westinghouse Co.).

NOTE.—Interlocks are shown in "open" position of contactors. Numbers adjacent to interlocks refer to contactors to which the interlocks belong.

fixed to spindle *A* of the master controller—when the hand-wheel is returned to a position beyond the normal " off " position.

Control system for dual operation on alternating-current and direct-current circuits. Certain passenger and freight locomotives on the New York, New Haven, and Hartford Railroad have to be capable of running over the tracks of the New York Central Railroad—which are supplied with direct current at 650 volts—in addition to operating on the single-phase 11,000-volt system of the New Haven and Hartford Railroad. The freight locomotives are each equipped with eight compensated-series motors, rated at 170 h.p. 275 volts (alternating current) and 200 h.p. 325 volts (direct current). The motors are arranged in pairs, and the motors of each pair are permanently connected in series. For alternating-current operation the four pairs are connected in parallel, while for direct-current operation the four pairs are arranged in two groups—the two pairs of each group being connected in parallel—and controlled on the series-parallel system with " bridge " transition.

The various combinations between the motors, rheostats, and transformer tappings are effected by electro-pneumatic contactors. There are in all 32 contactors, of which 17 are used for alternating-current control and 19 for direct-current control, four contactors being common to both control systems.

The control circuit is supplied from a 32-volt battery, and the whole of the control operations are effected by a single master controller in conjunction with a change-over switch.

The principal connections of the motor circuits and the control circuits are shown in Fig. 206, which, with the chart of switch operations, is self-explanatory.

The dual operation considerably complicates the wiring for the control and motor circuits. With similar locomotives, equipped for alternating-current operation only, nine running points are obtained with the use of 16 contactors, the number of tappings and the method of transition being the same as above. The control equipment of these locomotives, however, is 3·65 tons lighter than that of the above locomotives.*

* For detailed weights of the control equipments in the two locomotives, see a paper on "Trunk Line Electrification," by Mr. W. S. Murray (*Transactions of the American Institute of Electrical Engineers*, vol. 30, p. 1431).

CHAPTER XI

THE CONTROL OF THREE-PHASE RAILWAY MOTORS

General. The methods of obtaining a range of speeds from polyphase railway motors are: (1) rheostatic control, (2) control by changing the number of poles, (3) cascade control, (4) combined cascade and pole-changing control.

The **multi-speed methods of control** (viz. the pole-changing and cascade combinations) can be considered as the adaptation (and extension) of series-parallel control to polyphase motors. Thus the simple rheostatic and the two-speed changeable-pole, or cascade, control of two three-phase motors correspond, respectively, to the rheostatic and series-parallel control of two direct-current motors. The diagrams given in Fig. 107 (p. 168), showing the losses in the starting rheostats for rheostatic and series-parallel control also represent approximately the relative losses in the rheostats for the alternating-current cases, since, with changeable-pole motors, the losses in the rotor circuit, corresponding to a given starting torque, are inversely proportional to the number of poles. Four-speed changeable-pole control, however, will show greater economy in starting than the double series-parallel system in direct-current equipments, as in the former case four speeds are possible (which are usually in the ratio of either 1 : 1·5 : 2 : 3, or 1 : 1·33 : 2 : 2·66), while in the latter case only three speeds (in the ratio of 1 : 2 : 4, or 1 : 2 : 3) can be obtained.

Rheostatic control. This is the simplest but least efficient of the methods of regulating the speed of polyphase motors. Only one economical running speed is obtained, and approximately one-half of the energy supplied to the motors during the accelerating period is wasted in the rheostats. Owing to these features, the applications of simple rheostatic control are limited to those light locomotives and motor-coaches for which a single economical speed is sufficient and energy consumption is not of importance.

As, however, rheostatic control usually has to be employed in conjunction with the cascade and pole-changing methods, the starting rheostat forms an important part of three-phase control equipment.

The choice of rheostat and the grading of the resistance sections involve both general and special consideration, the former being similar to those discussed on pp. 255, 262, and the latter being concerned with the speed-torque characteristics of the polyphase motor when external resistance is connected in the rotor circuit.

The general relationship between the torque and slip of a polyphase motor (operating at constant voltage and frequency) is given by the equation

$$\mathfrak{T} = \frac{KsR}{R^2 + s^2X^2} = \frac{K}{X}\left(\frac{R/sX}{1 + (R/sX)^2}\right) \quad . \quad . \quad . \quad (20a)$$

where $\mathfrak{T}$ is the torque, K a constant, s the slip, R the total resistance per phase of the rotor circuit (i.e. the normal resistance, per phase, of

the rotor winding *plus* the external resistance), X the total reactance per phase of the rotor circuit at standstill ($s = 1$)—i.e. X is equal to the normal reactance per phase of the rotor winding at standstill together with any additional reactance that may be introduced by the external resistance and the connecting cables.

The general interpretation of this equation is shown graphically in Fig. 207, in which are given slip-torque curves for various values of the ratio R/X. Observe that for each value below unity of this ratio there

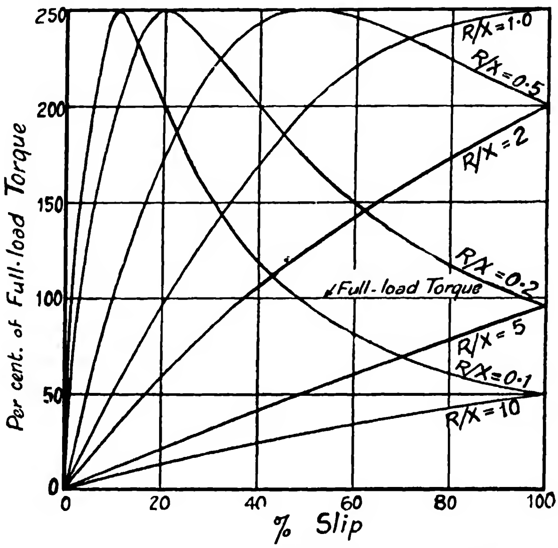


FIG. 207.—Torque-slip Curves for Polyphase Induction Motor.

is a particular slip at which the torque is maximum (this slip being given simply by the ratio R/X*), and that the maximum torque has the same value throughout.

The starting torque is given by

$$\mathfrak{T}_s = \frac{K}{X}\left(\frac{R/X}{1 + (R/X)^2}\right)$$

and is, therefore, a maximum when $R = X$. Observe that the starting torque corresponding to a given value of R/X is inversely proportional to X—the reactance of the rotor circuit. Hence any additional reactance that may be introduced into the rotor circuit by the insertion of external

* Thus if equation (20*a*) is differentiated with respect to s, and the first differential coefficient is equated to zero, we have

$$\frac{d\mathfrak{T}}{ds} = \frac{d}{ds}\left(\frac{KsR}{R^2 + s^2X^2}\right) = \frac{KR(R^2 + s^2X^2) - KsR(2sX^2)}{(R^2 + s^2X^2)^2} = 0$$

whence $R^2 + s^2X^2 = 2s^2X^2$

i.e. $R = sX$

Thus the torque is a maximum at the slip for which the reactance (sX) is equal to the resistance.

resistance adversely affects the maximum torque. Moreover, this additional reactance requires an increase in the external resistance to obtain a given torque at starting.

Therefore, when external resistance has to be inserted in the rotor circuit for the purpose of regulating the speed, it is important that no additional reactance be introduced into the circuit. This matter is of especial importance when the cascade connection is employed, as reactance in the secondary motor circuit adversely affects the power factor of the primary motor.

Of the two types of rheostat available—viz. metallic (or grid) and liquid—the liquid type, on account of its non-inductiveness, is preferable to the metallic type for the control of polyphase railway motors, especially when cascade working is to be adopted. Moreover, with a liquid rheostat the resistance can be cut out in such a manner that a uniform torque is obtained throughout the whole period of rheostatic acceleration. Against these advantages there are the following disadvantages: for a given equipment a liquid rheostat is heavier than a metallic rheostat; provision has to be made for cooling and circulating the liquid, or electrolyte, and for replacing loss due to evaporation; the electrodes require renewal periodically.

As developed for locomotive service, the liquid rheostat is automatic in its action, and is capable of dissipating a considerable amount of energy without overheating, while the controlling and regulating apparatus can readily be adapted for multiple-unit operation. The further consideration of these features, however, must be deferred until the general methods of control have been discussed.

Control by changing the number of poles. This method of control is the simplest of the multi-speed methods, and enables two, three, or four running speeds to be obtained from a single motor, or a group of motors connected in parallel. The three- and four-speed combinations, however, are only practicable if each motor has a squirrel-cage rotor.

With two-speed machines having slip-ring rotors the regulation of the torque and speed during starting and acceleration is effected by rheostatic control. If grid rheostats were adopted a different grading of the resistance sections would be necessary for each set of poles, and if multiple-unit operation were not required, the provision of duplicate rheostats would form the simplest solution.

With motors having squirrel-cage rotors the control of the torque during starting is effected by variation of the applied voltage, for which purpose auto-transformers with multiple tappings are suitable. The tappings may be successively connected to the stator winding by means of either a drum type controller or a group of contactors, the latter method being suitable when multiple-unit operation is required. In order to avoid short-circuiting the sections of the transformer winding, the transition from one tapping to the next is made through either a preventive coil or a resistance. Fig. 208 gives the connections and development of a drum-type controller in which a choking coil is inserted between adjacent tappings during transition.

Since the lowest voltage required from the transformers is of the order of one-third the line voltage, an auto-transformer possesses several

advantages over a transformer with separate windings. On three-phase circuits, two auto-transformers, connected in "V" (open-delta), can be used—instead of three transformers connected in star or delta—without unbalancing the system. Moreover, the V-connected auto-transformers only require two controllers (or groups of contactors) for each motor (or group of motors) supplied from the transformer.

Starting operations for changeable-pole motors. A four-speed equipment will be considered. The motors have two pole-changing stator windings (to give 16/8 and 12/6 poles) and squirrel-cage rotors. The control of the torque during starting is effected by variation of the applied voltage.

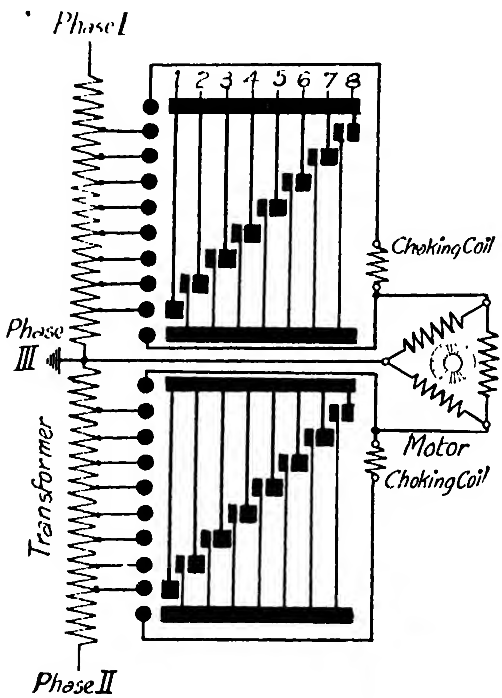


FIG. 208.— Connections and Development of Controller for Starting Induction Motor with Squirrel-cage Rotor.

The sequence of the control operations, in accelerating from stand still to full speed, is as follows—

(1) The reverser is set for the required direction of motion, and both pole-changing switches are closed to give the full number of poles for each winding.

(2) The motors are started on the lowest voltage of the auto-transformers, and the voltage is raised until the motors are operating with full voltage; the pole-changing switch for the 16-pole winding is then opened, thereby allowing the speed to rise to approximately the synchronous speed corresponding to 12 poles.

(3) Next, the voltage is reduced, the 8-pole winding is connected in parallel with the 12-pole winding, and the voltage increased again, when the 12-pole winding is opened.

(4) The voltage is again reduced, the 6-pole winding is connected in parallel with the 8-pole winding, the voltage is raised to normal, and the 8-pole winding is opened, thereby allowing full speed to be reached.

Cascade control. The cascade system of control requires two motors, which, for railway purposes, must have slip-ring rotors. At starting, and for low speeds, the secondary motor is supplied from the rotor of the primary motor, while, for higher speeds, both motors are operated in parallel. Hence two economical speeds are obtained. But when cascade control is used in conjunction with pole-changing windings three and four economical speeds are possible. For example, if each motor has a

pole-changing winding, giving two sets of poles in the ratio of either 2 : 3 or 3 : 4, *three speeds* (in the ratio of either 1 : 1·33 : 2 or 1 : 1·5 : 2) can be obtained by means of pole-changing control, together with cascade control in conjunction with *one* set of poles ; or *four speeds* can be obtained by means of pole-changing control together with cascade control in conjunction with *both* sets of poles.

Two-speed cascade control. The motors are operated in cascade for the lower speed and in parallel for the higher speed. For parallel operation each motor must have the same ratio of transformation—since the rotors are connected in parallel as well as the stators—but for cascade operation the ratio of transformation of the secondary motor must be unity if the

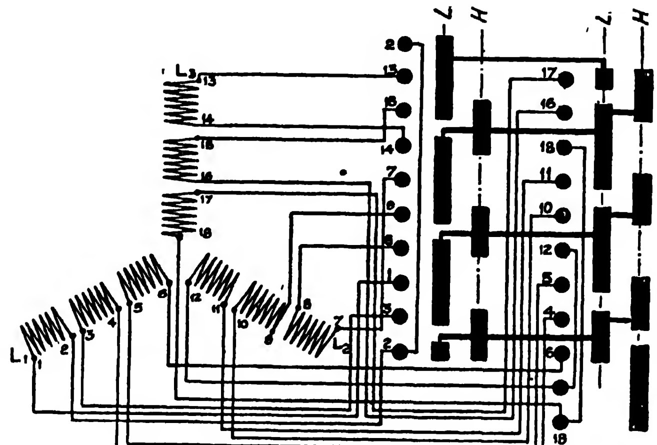


FIG. 209. Connections and Development of Re-grouping Switch for 12-pole Motor. (*L*, *H*, switch positions for low and high voltages, respectively.)

same starting rheostat is to be used for both parallel and cascade operation.

With high-voltage motors the ratio of transformation is greater than unity. Hence if both motors are designed for the same ratio of transformation, cascade operation will necessitate re-grouping the stator winding of the secondary motor for a 1 : 1 ratio of transformation. In cases where this is impracticable, the "inverted" cascade connection must be employed and the rheostat (which must be of the metallic type) must be re-grouped for cascade operation. The inverted cascade connection is formed by inverting the connections of the secondary motor (i.e. the rotor of this motor is connected to the rotor of the primary motor and the stator is connected to the starting rheostat.

The switch for re-grouping the stator winding is usually of the drum type and is mounted on the frame of the motor. Fig. 209 gives the connections and development of a suitable switch for re-grouping the windings of a 12-pole motor. Each phase of the stator winding consists of six groups of coils—one group per pair of poles. For cascade working these coils are connected in three parallel sets (each set comprising two groups

of coils in series) and the phases connected in delta ; while for parallel operation the coils are connected in series and the phases connected in star.

The change of connections from cascade to parallel, and vice versa, is effected by a change-over switch, which is usually of the drum type. This switch and the re-grouping switch are operated pneumatically.

Fig. 210 gives the connections and development of a drum-type change-over switch for two-speed cascade-parallel control.

The control operations during starting and accelerating from standstill to full speed are—

(1) Set reverser for the desired direction of motion.

(2) Set change-over and re-grouping switches on secondary motor

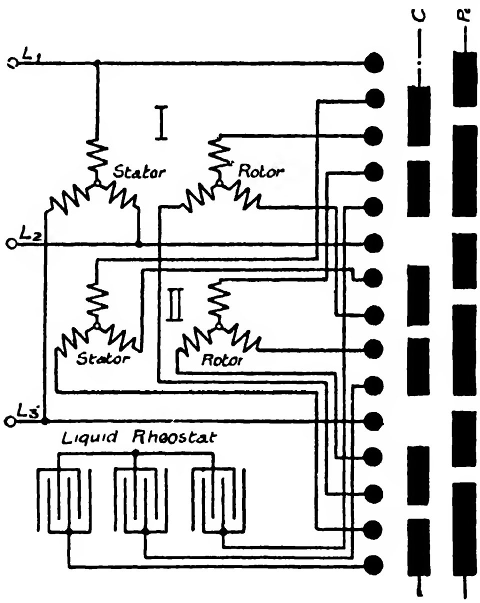


FIG. 210. Connections and Development of Change-over Switch for Two-speed Cascade-parallel Control.

for cascade operation; connect stator winding of primary motor to supply.

(3) Cut out resistance until the rheostat is short-circuited.

Combined cascade and pole-changing control. In this method the primary and secondary motors are each wound for the same number of poles, but the windings are so arranged that the number of poles can be changed. If the poles are changed in the ratio of 2 : 1, the speeds obtainable will be in the ratio of 1 : 2 : 3 : 4. This variation of speed is too great for general railway service, and a maximum variation of 1 : 3 is generally sufficient for all conditions of passenger service.

Hence it will be necessary to change the poles in the ratio of either 1·33 : 1 (i.e. 8 : 6) or 1·5 : 1 (e.g. 12: 8), so that the four speeds obtainable are in the ratio of 1 : 1·33 : 2 : 2·66, or 1 : 1·5 : 2 : 3 respectively.

In Chapter VI we described two pole-changing windings to give 8 and 6 poles. The simpler winding (Fig. 78) requires a three-phase supply when connected to give 8 poles and a two-phase supply when connected to give 6 poles. The other winding (Fig. 77) operates throughout with three-phase current. In both cases the provision for cascade and parallel operation with both sets of poles involves complication in the control apparatus.

Considering first the winding which operates throughout with three-phase current, cascade operation will involve either the re-grouping of the stator winding of the secondary motor for a ratio of transformation of unity, or the use of the inverted cascade connection and the re-grouping of the sections of the (metallic) rheostat. With high-voltage motors the

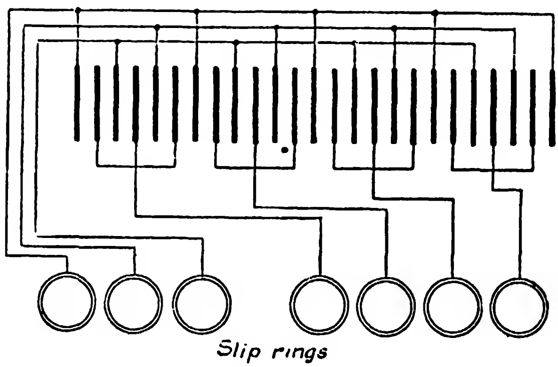


FIG. 211.—Connections of Rheostat Electrodes to Slip-rings for Three-phase and Two-phase Operation with Rotor Winding of Fig. 80.

inverted cascade connection necessitates the insulating of the rheostats to withstand the line voltage.

With the alternative pole-changing winding—operating with three-phase current for 8 poles and two-phase current for 6 poles—cascade operation will involve a suitable three-phase/two- (or four-) phase rotor winding and a suitable rheostat. A single rotor winding to meet the requirements is described in Chapter VI, and a liquid rheostat solves satisfactorily the rheostat problem. The seven slip rings (Fig. 81) are connected to the electrodes of the liquid rheostat in the manner shown in Fig. 211.

The rheostat must be suitable for either the three-phase or the two-phase rotor circuits. A reference to Fig. 81 will show that when the motor is operating with three-phase current (i.e. 8 poles), there will be no potential difference between the two- (or four-) phase slip-rings—since these are connected to the four neutral points of the winding—while, with two-phase operation (i.e. 6 poles), all the three-phase slip-rings will be at the same potential.

The two-phase current for supplying the stators of the motors may be obtained from the three-phase supply by means of two auto-transformers, connected according to the Scott (or " T ") system, as indicated

in Fig. 212). With this method of connection transformers of relatively small capacity are necessary, since the largest portion of the input to the motor is supplied directly from the supply lines. A reference to Chapter VI (p. 136) will show that, if the stator winding is star-connected for three-phase working, and the full line voltage is used for two-phase operation, the flux in the latter case is about 34 per cent greater than that in the former case. The normal flux, however, can readily be obtained by means of tappings on the auto-transformers.

Reverting to the circuit diagram of Fig. 212, phase I of the motor is connected across the lines BC, or, if normal flux is required in the motor, to tappings EF (giving 75 per cent of the line voltage) on the

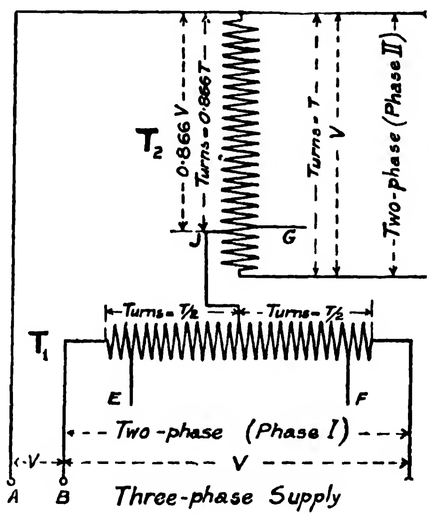


Fig. 212.—Connections of Three-phase/Two-phase Auto-transformers.

auto-transformer T_1; while phase II is supplied through auto-transformer T_2, which is connected to the line A and to the centre point of transformer T_1.

To obtain equal voltages on each phase of the motor, each transformer must have the same number of turns. The turns on transformer T_2, between the tapping (J)—to which the centre of transformer T_1 is connected—and the end (D) of the winding must be 0·866 ($= \frac{1}{2}\sqrt{3}$) of the turns on transformer T_1, while the turns between tapping G and the end D must be 0·75 of the turns on transformer T_1 (i.e. the same as the turns between tappings E and F).

Examples of combined cascade pole-changing control. The four-speed cascade pole-changing methods of control have been applied by the Società Italiana Westinghouse and the Tecnomasio Italiano Brown-Boveri to large express passenger locomotives in service on the Italian State Railways. For the low-frequency sections of the railway system

the locomotives are equipped with two 1300 h.p. motors which are wound for the full line voltage (3300 volts).

The **Brown-Boveri** equipments operate with three-phase current throughout, the inverted cascade connection being employed for cascade operation.

The rheostats are arranged in three groups—one group for each phase—which are insulated from one another and connected to the change-over switch. Each group is divided into eight sections, the resistances of corresponding sections being the same for each phase. The sections are cut in and out of circuit by means of a group of 30 contactors which are actuated by a cam-shaft, the latter being chain-driven from a three-cylinder pneumatic engine. The cam-shaft has 11 operating positions (or notches) in addition to an "off" position.* On the first six notches the rheostat sections are cut out simultaneously from each group, and the phases are balanced; but on the remaining notches the sections are cut out successively, and, in consequence, an unbalancing of the phases occurs on some of these notches.

The four positions of the change-over switch give the following combinations of motors and rheostats—

(1) *Lowest speed—8 poles, cascade.* Rotor of primary motor connected to rotor of secondary motor; stator of secondary motor (grouped in delta†) connected to rheostats (grouped in star).

(2) *Lower intermediate speed—6 poles, cascade.* Rotor of primary motor connected to rotor of secondary motor; stator of secondary motor (grouped in star) connected to rheostats (grouped in star).

(3) *Higher intermediate speed, 8 poles, parallel.* Stator of secondary motor (grouped in star) connected to line; rotors of both motors paralleled and connected to rheostats (grouped in delta).

(4) *Highest speed—6 poles, parallel.* The combinations between motors and rheostats are the same as for position (3).

The stator pole-changing switches, change-over switch, rheostat re-grouping switch, and rheostat contactors are oil immersed, and are operated pneumatically.

The **Italian-Westinghouse** equipments employ the three-phase/two-phase method of pole-changing and automatic liquid rheostats. The change-over, pole-changing, and re-grouping switches are of the drum type; they are mounted on the top of the motors (see Fig. 85) and are operated electro-pneumatically.

The four positions of the change-over switch give the following combinations—

(1) *Lowest speed—8 poles, cascade.* Three-phase slip-rings of primary motor connected to re-grouping switch of secondary motor; three-phase slip-rings of secondary motor connected to rheostat.

(2) *Lower intermediate speed—8 poles, parallel.* Stator winding of secondary motor connected in parallel with stator winding of primary motor; three-phase slip-rings of primary motor connected in parallel with those of secondary motor.

* The first operating position is arranged to close the oil switch controlling the stator circuits.

† The delta and star combinations of the stator winding of the secondary motors are made by a separate switch.

(3) *Higher intermediate speed*—*6 poles, cascade.* Two-phase slip-rings of primary motor connected to re-grouping switch of secondary motor; two-phase slip-rings of secondary motor connected to rheostat.

(4) *Highest speed*—*6 poles, parallel.* Stator winding of secondary motor connected in parallel with stator winding of primary motor; two-phase slip-rings of primary motor connected in parallel with those of secondary motor.

Operation of three-phase motors on single-phase systems. In Chapter I mention was made of a combined single-phase and three-phase system—known as the **split-phase system**—in which three-phase motors are supplied from a single-phase distributing system by means of a transformer and phase-converter carried on the locomotive or vehicle. This system enables large locomotives to be equipped for heavy regenerative braking and to operate from a single-phase system.

The **phase-converter** is virtually a two-phase motor operated either without mechanical load or with a light direct-connected load, such as a blower or exciter; it may be of either the induction type with squirrel-cage rotor, or the synchronous type with revolving field excited with direct current. The synchronous type possesses the important advantage that the power-factor can be controlled—in the same manner as that of a synchronous motor—and, in consequence, the system can be operated at unity power-factor. With each type the machine must be brought up to approximately synchronous speed—by means of an auxiliary motor—before being connected to the supply system. When connected to the supply system the converter will operate as a single-phase induction (or synchronous) motor and a phase transformer; the energy supplied to the phase, or winding, which is connected to the supply system being equal to the energy transformed in the other phase *plus* the energy required to supply the losses.

The general **principle of the phase-converter** is that if one phase of a polyphase induction motor is supplied with single-phase current after the rotor has been brought up to normal speed the magnetic reactions will produce a rotating field, which will induce E.M.Fs. in the other portions of the stator winding of the same phase relations as if these windings had been supplied with polyphase current. Thus, with a two-phase stator winding, if one phase is supplied with single-phase current after the rotor has been run up (by a separate starting motor) to normal speed, the E.M.F. induced in the open phase of the winding has a phase difference of 90° with respect to the E.M.F. induced in the phase connected to the supply.

The manner in which a three-phase motor is supplied from a single-phase supply system by means of a two-phase converter is shown diagrammatically in Fig. 213. The main transformer is shown at T, and the centre point of the secondary winding (C) is connected to one of the stator windings (D) of the phase converter, the other end of this winding being connected to one of the terminals (F) of the three-phase motor. The other terminals (G, H) of this motor are connected to the terminals (A, B) of the secondary winding of the transformer, to which terminals are also connected the second stator winding (E) of the phase-converter. Now, when the phase-converter is in operation, there is induced in the

winding D an E.M.F. which has a phase-difference of 90° from the E.M.F. at the terminals A, B of the transformer. Hence, by arranging that the E.M.F. induced in phase D shall be 0·866 ($= \frac{1}{2}\sqrt{3}$) of the E.M.F. across A, B, we have—by connecting D to the centre point (C) of the transformer—the same conditions as exist in the standard method of three-phase to two-phase transformation. Therefore three-phase current may be obtained from the terminals A, B, F.

As actually constructed the phase-converter is more complicated than we have indicated above, since features must be incorporated into its design for annulling the inductive effects due to the load current; while, to maintain balanced three-phase voltages under load, the tapping (C) on the transformer must be shifted from the centre point of the winding.

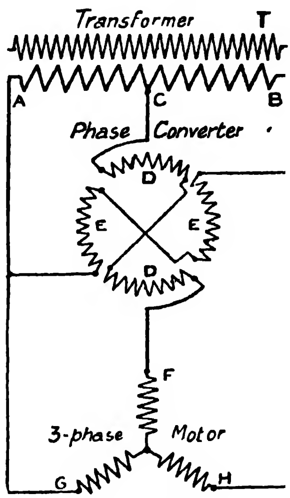


Fig. 213.—Diagram of Circuits of Phase-converter.

The **control of three-phase motors supplied from a phase-converter** is identical with that of similar motors supplied from a three-phase system, the method adopted in a given case depending on the number of speeds required.

Since a transformer forms an essential part of the split-phase system the operating voltage of the motors may be selected at any convenient value, which for motors of medium output (500 h.p.) may be from 700 to 1000 volts. This voltage is convenient for the control apparatus, as standard contactors may be used for breaking the circuits, and drum-type controllers may be used for the pole-changing switches. Moreover, the motors may be designed for a 1 : 1 ratio of transformation so that re-grouping switches are not required for cascade control.

The additional control apparatus required in conjunction with the phase-converter comprises: (1) a "tap-changer," for effecting the changes in the tappings of the main transformer—so as to maintain balanced three-phase voltages at various loads; (2) switch-gear for starting the phase-converter.

The "tap-changer" may consist of a group of contactors and a preventive coil, this apparatus being essentially of the same nature as that used for the voltage control of single-phase motors, and any of the closed-circuit transition methods discussed in Chapter IX (pp. 266–271) can be adopted.

The switch-gear for starting the phase-converter will depend on the type of converter and the method of starting. With both (synchronous and induction) types the starting motor is usually of the single-phase series type. At starting, this motor is connected in series with the "running" phase of the converter, and the combination is connected to a section of the transformer winding, a single contactor being used for this purpose. As the set approaches synchronous speed the converter is connected directly to the transformer and the motor is cut out. These operations can be arranged to take place automatically.

In the case of a synchronous phase-converter a shunt winding may

be added to the starting motor so that the latter may be converted into an exciter. The shunt winding, however, must be separately excited. During starting this winding must be broken up into sections in order to avoid a high voltage being induced in the shunt circuit by the alternating flux. The set is started in the above manner, the field winding of the converter being short-circuited while the set is running up to speed. When the converter reaches approximately synchronous speed the starting motor is cut out and the field is excited, thus enabling the converter to pull into synchronism. These operations are performed automatically by a change-over switch, which is operated electro-pneumatically, the sequence of operations being as follows: (1) starting motor cut out, (2) armature circuit of starting motor (or exciter) connected to field circuit of converter and the short-circuit across the latter removed, (3) shunt field winding of exciter connected to source of excitation.

Typical Control Apparatus for Multi-speed Methods of Control

Control apparatus for multi-speed three-phase equipments has been developed almost exclusively for use on electric locomotives. Notwithstanding the apparent complexity of the combinations to be effected by this apparatus in some of the multi-speed methods of control (e.g. the two-speed and four-speed cascade-parallel methods), the control equipment is characterized by its general simplicity and the small number of parts.

This simplification is obtained by the adoption of high-voltage motors and automatic liquid rheostats, together with the use of compressed air for performing the principal operations of the control apparatus.

Therefore no switches are required to break heavy currents, and by confining the interruption of the main primary circuits to the reverser, the pole-charging, change-over, and re-grouping switches have to be designed with reference to current-carrying capacity and insulation only. Consequently these latter switches may be of the controller or drum type,* which type of switch, for high-voltage equipments, has obvious advantages over a number of separate contactors.

Automatic liquid rheostat. The most interesting portion of the control equipment is the automatic liquid rheostat. The liquid rheostat was first applied to railway purposes (in about 1901) by Ganz & Co. in connection with the equipment of the Valtellina line of the Italian State Railways.† The experience obtained on this line proved that a liquid rheostat possesses several advantages for the control of three-phase motors on the cascade system. Improvements have been introduced into later rheostats by Ganz & Co. and the Società Italiana Westinghouse so that, at the present day, the liquid rheostat has a wide application for three-phase locomotives.

* With a line voltage of 3000 volts, the full load current of a 1000-h.p. three-phase railway motor is approximately 160 amperes. This current can be carried continuously by a controller finger and segment 1¼ in. wide.

† See *The Electrician*, vol. 51, p. 19, for a description of the original equipment on this line.

The **general features of liquid rheostats** for three-phase railway motors are—

A number of electrodes, of iron plate, are suspended in the upper part of a tank into which a solution of carbonate of soda can be admitted from a storage tank (at a lower level) by means of compressed air, which is supplied to the latter tank through suitable valves. The rate at which the liquid rises between the electrodes (and therefore the rate at which the resistance is cut out) is governed by the air pressure in the storage tank, which pressure is regulated by a valve or combination of valves operated by the motor current. When the liquid has risen to a certain height, the electrodes are automatically short-circuited by a special switch. In the more recent rheostats, provision is made for an efficient circulation and cooling of the liquid in order to reduce evaporation. Rheostats of this type have been standardized for locomotive equipments on the Italian State Railways, and have recently been adopted by the Westinghouse Co. for controlling the three-phase motors on the Norfolk and Western split-phase locomotives, notwithstanding that the grid type of rheostat is the accepted standard for all railway and industrial purposes in America.

The **latest type of rheostat** constructed by the **Società Italiana Westinghouse** for the express passenger locomotives (type F.S. 330, class 2–6–2) of the Italian State Railways is illustrated in Fig. 214.

The upper portion of the corrugated tank *A* contains the electrodes (the terminals of which are visible in the illustration), while the lower portion of the tank forms the reservoir for a solution of sodium carbonate.* This portion of the tank communicates, by means of the pipe *B*, with the pneumatic head-piece *C*, which contains the valves for controlling the supply of compressed air to the pipe *B* and the reservoir. The valves performing this function are two in number, one for admission and one for exhaust, and are of the pneumatic-relay type. They are controlled by means of electrically-operated pilot valves, which are energized from an automatic regulator, to be referred to later. These pilot valves, of which two are visible in Fig. 214, are of the standard Westinghouse type.

When the liquid rises in the electrode chamber to a predetermined height, the electrodes are automatically short-circuited by the switch *D*, This switch is operated by compressed air, and the valve controlling it is actuated by a float in the electrode chamber. At the same time as the electrodes are short-circuited, two other switches are operated. One of these switches controls a signal lamp in the driving compartment of the locomotive—thereby indicating to the driver that the rheostat is short-circuited—while the other switch opens the circuit of the motor driving the circulating pump.

When the rheostat is in operation, a centrifugal pump—located in the reservoir—maintains an efficient circulation of the liquid between the reservoir and the electrode-chamber, thereby preventing local heating and evaporation of the liquid. The pump is driven by a three-phase induction motor *E* (with squirrel-cage rotor), which is automatically controlled by a switch *F*, so that the motor is only in operation while power is being absorbed in the rheostat.

* The rheostat illustrated in Fig. 214 is designed for controlling two 1300-h.p. motors. The reservoir contains 1550 lb. of fluid.

The automatic regulator (which is shown at *G* in Fig. 214) is designed to regulate the resistance of the rheostat for a ***constant watt-input to the motors***.* In construction, the regulator is similar to a small two-pole induction regulator; the stator consists of a laminated core, with a two-pole winding connected in series with the earthed phase of the motors; the rotor consists of a double T-shaped laminated core, with a shunt winding excited from the transformer supplying the control circuits. The torque between the stator and rotor is, approximately,

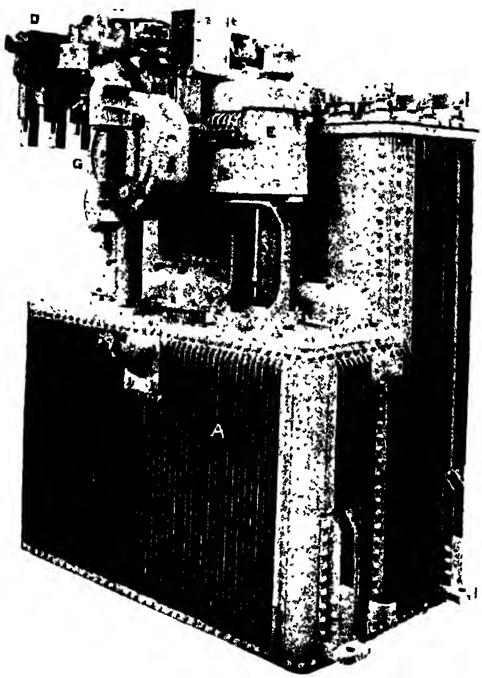


FIG. 214. Società Italiana Westinghouse Automatic Liquid Rheostat for Three-phase Electric Locomotives.

proportional to the watts input to the motors, and is balanced by a spring, the tension of which can be regulated by the driver (from the master controller) so as to predetermine the power input to the locomotive.

The motion of the rotor is restricted between two stops, adjacent to which are contacts connected in series with the magnet coils of the pilot valves which control the admission of air to the reservoir tank.

In starting, the driver applies a tension to the spring—by means of a handle on the master controller—which rotates the rotor so as to

* In the rheostats supplied with the earlier (1909) freight locomotives (type F.S. 050, class 0–10–0) the regulator was designed to regulate for constant current input. The present type of regulator was developed so that the acceleration of locomotive should not be influenced by variations of the line voltage.

energize the pilot valve admitting air to the reservoir. The liquid then rises in the electrode chamber, thereby increasing the electrical input to the motors and, consequently, the torque between the stator and rotor of the regulator. When this torque just balances the tension of the spring, the rotor assumes its neutral position and interrupts the circuit of the pilot valve. If the motor input increases, the torque of the rotor exceeds that of the spring, and the pilot valve exhausting the air from the reservoir is energized, thereby lowering the level of the liquid in the electrode chamber and reducing the motor input.

In order to obtain a constant input to the motors when they are connected in cascade and also in parallel, the stator winding of the regulator is wound in two sections, which are connected in series for the

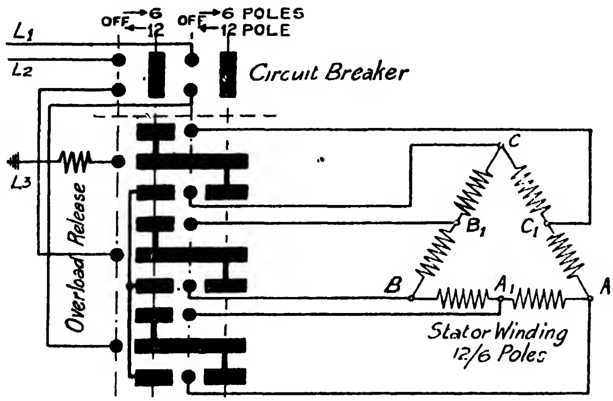


FIG. 215. Connections and Development of Pole-changing Switch.

cascade connection of the motors and in parallel for the parallel connection of the motors, these groupings being effected by means of fingers and segments on the change-over switch.

Pole-changing switches. These are usually of the drum type and are operated pneumatically.* The switches are not intended for breaking the circuit, which operation is performed either by a double-pole oil switch combined with the pole-changing switch, or by the reverser (which, in this case, is designed for circuit breaking). The former method is adopted for four-speed changeable-pole equipments, as the two pole-changing windings may then be used either in parallel or singly. Separate pole-changing and circuit-breaking switches are used for each pole-changing winding. Fig. 215 shows the connections and development of this type of combined pole-changing switch and circuit breaker for motors in which the poles are changed in the ratio of 2 : 1.

Fig. 216 illustrates a Brown-Boveri oil-immersed switch for pole changing, according to the method shown in Fig. 77.

This switch is designed for a 3300-volt circuit and is of the drum

* For multiple-unit operation, the admission of air to the pneumatic cylinders would be performed by electrically controlled pilot valves, similar to those adopted in the Westinghouse electro-pneumatic control system.

type, the contacts being oil-immersed. The 39 fingers are arranged in four groups, spaced 90° apart, and each group of fingers is carried on an insulated steel bar which is fixed to the end brackets carrying the bearings for the shaft. The segments (*e*) are clamped to four insulated steel bars, spaced 90° apart, the ends of the bars being supported by spiders fixed to the shaft. The latter is operated through gearing by

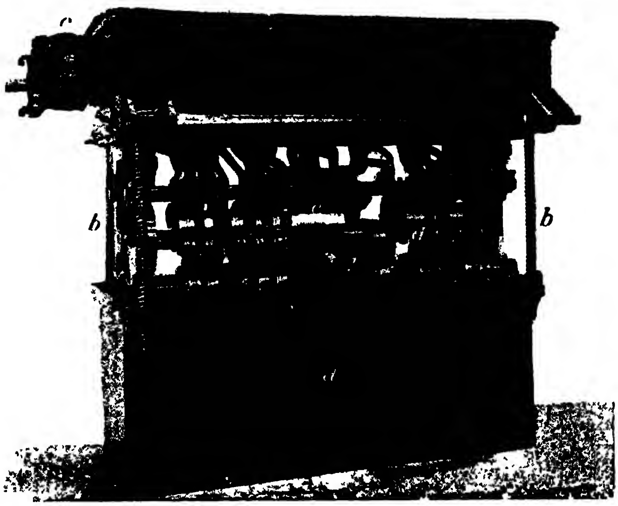


FIG. 216.—Brown-Boveri Oil-immersed Pole-changing Switch.

(*a*, oil tank (lowered); *b*, screws for raising and lowering tank; *c*, pneumatic cylinders; *d*, fingers; *e*, segments)

pneumatic cylinders (*c*), which also operate an interlocking drum located in the upper portion of the frame.

The special arrangement of the fingers and segments in four groups results in a compact switch notwithstanding the large number of contacts, while the immersion of the latter in oil ensures adequate insulation.

Re-grouping and change-over switches for cascade control. For two-speed cascade-parallel equipments, the change-over switch may be combined with the re-grouping switch when the latter is of the drum type. Hence, with the usual method of pneumatic operation, only one double-acting pneumatic cylinder is required for effecting the cascade and parallel combinations of the motors and rheostat.

Reversers. To reverse the direction of rotation of a three-phase motor, two of the line wires must be interchanged with respect to two terminals or phases of the stator winding. Since in all three-phase traction systems one phase of the supply and one terminal of each motor is permanently earthed, the reversal of direction of rotation involves simply the interchange of the connections between the trolley wires and the corresponding terminals of the motor.

In pole-changing equipments in which the pole-changing switch is

combined with a circuit breaker, the reverser is of the drum type, and the arrangement of the fingers and segments is identical with that in a reverser for a direct-current equipment.

With cascade and combined pole-changing-cascade equipments, the reverser usually fulfils the combined functions of a reversing and circuit-breaking switch. For low-voltage circuits contactors are usually employed, but for high-voltage circuits either a double-pole, double-throw oil switch, or a special capstan-type air-break switch must be employed. The capstan-type, air-break switch is used extensively on the 3000-volt lines of the Italian State Railways.

Master controller. In multi-speed control equipments the master controller possesses several features of interest. In many cases the operation of the various switches is carried out entirely by means of compressed air, and the master controller then becomes a combination of valves.

For multiple-unit operation the pneumatic cylinders of the various switches must be controlled by electro-magnetic valves. The master controller must energize the magnets of these valves and also set the automatic regulator of the rheostat for the required acceleration. These operations can be performed by two handles, viz. one handle controlling the speed and the direction of motion, and another handle controlling the acceleration.

On the other hand, with "all-pneumatic," non-multiple unit control equipments, three handles will be required, as the valves controlling the pneumatic cylinders of the various switches must be operated directly from the controller.

Electro-pneumatic controllers have been developed by the Società Italiana Westinghouse and the Westinghouse Co., while pneumatic controllers have been developed by Ganz & Co.* and Brown, Boveri & Co.

In the electro-pneumatic system the control circuit is supplied with either single-phase current—at from 80 to 100 volts—or direct current at a low voltage (obtained from accumulators). Hence the master controller has to handle only small currents at low voltage.

* For description and illustrations of Ganz pneumatic controllers, see *L'Éclairage Électrique*, vol. 43, p. 487.

CHAPTER XII

REGENERATIVE BRAKING: GENERAL CONSIDERATIONS

Mechanical regenerative braking. The energy output from the motors of an electric train, operating on a level track, is expended in (1) accelerating the train, and (2) supplying the losses due to the resistances to motion. When the train is running at constant speed, the kinetic energy which it possesses is equal to the energy expended in acceleration. During coasting a portion of this energy is utilized for propulsion. Hence, coasting may be considered as a form of **mechanical regenerative braking** or recuperation of energy. Generally, the greater the ratio of the coasting period to the total running period the lower will be the energy consumption. But prolonged coasting will result in a low schedule speed, and, if the original schedule speed is to be maintained, an increase in the acceleration will be necessary, which will usually involve the use of larger motors, so that the saving in energy consumption may be neutralized by the increased train weight and the additional cost of the equipments. With modern urban and suburban traffic conditions, the coasting period is from 20 per cent to 50 per cent of the total running period, and consequently a large percentage of the acceleration energy has to be wasted in the brakes.

By suitably **grading the track** the kinetic energy of the train may also be utilized in doing work against gravity. When the train is brought to rest it will, therefore, possess a certain amount of potential energy which can be utilized during the descent of the train to the level. This form of mechanical regenerative braking is adopted on some of the London tube railways, the tracks being graded in the manner shown in Fig. 217.* As far as the conditions of construction will permit, the station platforms are arranged at the same level. The tracks between the stations are constructed with a 1 in 60 (1·66 per cent) *up* gradient on the entering side; a 1 in 30 (3·3 per cent) *down* gradient on the leaving side, and a level stretch between the gradients.† The lengths of the gradients are so arranged that power is cut off from the motors when the train is on the level. Mechanical regenerative braking occurs while the train is ascending the 1 in 60 gradient, and the final stage in the braking is performed by the application of the mechanical brakes as the train enters the station.

In the case of the Central London Railway the gradients result in a recuperation of 14 watt hours per ton mile, which corresponds to about one-third of the energy consumption of a seven-car train operating at a schedule speed of 14 ml.p.h.‡

The total economy, however, is not simply represented by the

* Regenerative braking—whether mechanical (by means of gradients) or electrical—is an important feature in tube railways, where dust should be specially avoided. In the London tube railways, the brake-block wear is reduced by more than 50 per cent by the adoption of a graded track in contrast to a level track.

† The reason for the difference in the *up* and *down* gradients is, that a gradient of 1 in 30 against a train would be very disadvantageous in the case of a signal stop.

‡ These values were obtained in 1903 with the original motor-coach trains weighing 120 tons, the average energy consumption of which was found to be 43 watt hours per ton mile when running the service at a schedule speed of 14 ml.p.h.

decreased energy consumption of the train, because the service can be run with smaller equipments than a similar service on a level track. Economies will, therefore, be effected in the interest and depreciation charges on the equipments and the rolling stock. Moreover, the improvement in the load-factor at the power house, due to the lower peak load, enables the generating plant to be operated at a high average efficiency, which is conducive to low generating costs.

But these economies will be sacrificed if the service is run in any other than the predetermined manner for which the graded sections of the track is designed. Hence if an increase in schedule speed becomes necessary, owing to traffic requirements, a higher acceleration, together with a higher maximum speed, must be employed, which, in general, will entail alterations in the train equipments.

Electric regenerative braking possibilities on level track. Although graded track construction is quite practicable for tube railways, it is

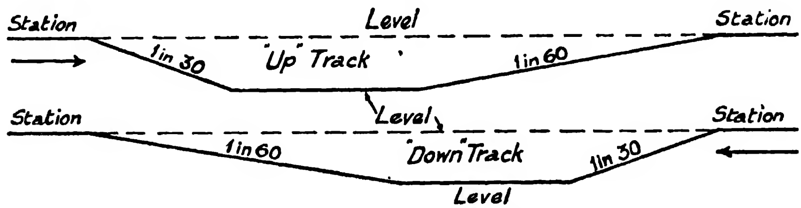


FIG. 217.- Grading of Track on Central London (Tube) Railway.

scarcely practicable for surface railways. Hence, if reductions are to be effected in the energy consumption of level-track surface lines by means of regenerative braking, the electrical equipment must be utilized for this purpose, the motors being operated as generators during the period of retardation, and the power generated being returned to the supply system.

The **energy which it is possible to recuperate** under these conditions will depend upon (1) the train speeds at which regenerative braking commences and ceases, (2) the efficiency of the electrical equipment and line conductors to the point of utilization of the recuperated energy, (3) the train resistance. The train speed at which regenerative braking ceases will depend upon a number of factors connected with the motor equipment and the system of control, but, in general, the lowest speed at which regenerative braking is practicable for a given combination of motors will be slightly higher than the speed (for this motor combination) at the end of the rheostatic-accelerating period. With series-parallel control and motor equipments suitable for suburban service the lowest speed at which regenerative braking would be practicable is of the order of 10 miles per hour. Hence if average values are assumed for train resistance, efficiency of electrical equipment, and the ratio (effective train weight/actual train weight), we can, by the application of the principles given in Chapter III, derive curves similar to those of Fig. 218, showing the relationship between the recuperated energy and the speed at which regenerative braking commences.

In deriving the curves of Fig. 218 we have assumed a constant train resistance of 14 lb. per ton, an effective train weight 10 per cent greater than the dead weight, an average efficiency during regeneration of 80 per cent, and a uniform retardation of 1 ml.p.h.p.s. during regeneration. The method of calculation is as follows—

The kinetic, or stored, energy at a train speed of V ml.p.h. is equal to $0{\cdot}0283V^2 \times 1{\cdot}1$, or $0{\cdot}031V^2$ watt hours per ton of train weight.

The energy expended against train resistance is equal to $2 \times 14 \times D'$

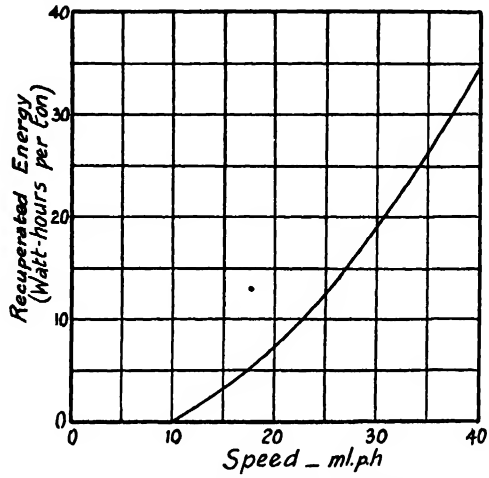


FIG. 218.—Energy Recoverable by Regenerative Braking on Level Routes.

$= 28D'$ watt hours per ton of train weight, where D' is the distance (in miles) run during recuperation (i.e. between the speed V and 10 ml.p.h.).

[NOTE. $D' = \frac{1}{2}(V - 10)^2/3600\beta_r$, where β_r is the retardation (in ml.p.h.p.s.) during regenerative braking.]

Hence the energy available for recuperation is equal to

$$0{\cdot}031(V^2 - 10^2) - 14(V - 10)^2/3600\beta_r$$

watt hours per ton of train weight, and the energy returned to the supply system is equal to

$$0{\cdot}8[0{\cdot}031(V^2 - 10^2) - 0{\cdot}0039(V - 10)^2/\beta_r]$$

watt hours per ton of train weight.

For example, if regenerative braking commenced at a speed of 30 ml.p.h. (which would be quite practicable in suburban service) the recuperated energy would be

$$0{\cdot}8[0{\cdot}031(30^2 - 10^2) - 0{\cdot}0039 \times 20^2] = 19{\cdot}8$$

watt hours per ton of train weight. Hence with a service having 0·75 stops per mile (for which the specific energy consumption without regenerative braking may be of the order of 70 watt hours per ton mile) the approximate energy consumption may be $70 - 19{\cdot}8 \times 0{\cdot}75 = 55$ watt hours per ton mile. Thus in this case the saving of energy due to regenerative braking is 21·4 per cent.

Disadvantages and advantages of regenerative braking on level routes. In practice a number of difficulties and disadvantages are involved in

the application of regenerative braking to level routes. The disadvantages, in so far as direct-current equipments are concerned, are briefly—

The motors are larger, heavier, and more costly than those for ordinary equipments, thereby resulting in more costly mechanical parts (e.g. trucks), an increase in the weight of the train, and possibly an increase in the number of motors. Additional equipment is necessary for the purpose of controlling and safeguarding the regenerative action of the motors and to obtain suitable regenerative characteristics. These features result in increased first cost of the trains, increased maintenance charges on the electrical equipment, and increased complication in the control and method of operation. Moreover, difficulties in the operation of the substations may occur should the recuperated energy exceed the energy output from the substation.

To offset the disadvantages there are the following advantages—

Reduced energy consumption; reduced wear of brake shoes and wheel tyres; lower maintenance costs for these items; relatively small amount of brake dust produced when the mechanical brakes are applied.

In the majority of cases, however, and especially with motor-coach train, the increased cost of the train equipments and the additional features necessary to obtain regenerative braking, combined with the increase in the maintenance costs of the electrical equipment, may entirely off-set the economies in the energy consumption and the other items.

Practical results. It will be of interest to consider briefly what economies have actually been obtained in practice with regenerative braking under **suburban service** conditions. A train, with direct-current multiple-unit equipment and arranged for regenerative braking, when tested* under normal service conditions on the Paris Metropolitan Railway, showed an energy consumption 20 per cent lower than that of a standard equipment (the respective figures being 48 and 60 watt hours per ton mile); while, during braking, the energy returned to the supply system reached 30 per cent of the energy used in acceleration.

The train was equipped with standard 175-h.p., 600-volt, traction motors, together with a booster-exciter set (for each pair of traction motors) and control apparatus. The booster-exciter set was used both during regenerative braking and at starting. The weight of this set, together with the controlling apparatus, was 4070 lb., but, due to the elimination of starting rheostats, the net additional weight of the regenerative equipment for a pair of motors was 3080 lb.

Experience with **regenerative equipments on tramways** has shown that on level routes the energy consumption is about 10 per cent lower than that of a standard (series motor) equipment, the operating conditions being similar in each case. With undulating routes the saving may be of the order of 20 per cent.

Electric regenerative possibilities on main-line and mountain railways. The operating conditions on main line railways having long gradients and on mountain railways are very favourable to electric regenerative

* See *Electric Railway Journal,* vol. 43, p. 304.

braking* owing to (1) the relatively large amount of energy available during the descent of the gradients, (2) the exclusive use of electric locomotives, (3) the operating conditions permitting the use (when desirable) of motors having constant-speed characteristics. In these cases, even when direct-current series motors are employed, the additional equipment necessary for regenerative braking adds but a small percentage to the cost of the locomotive.

The **advantages** due to regenerative braking on these railways are greater than those obtained on level routes. Thus, in addition to the saving of energy, there are large savings in the maintenance of the mechanical brakes and wheel tyres. Moreover, owing to the mechanical brakes being used only to a small extent—and, in some cases, not at all—during the descent of gradients, the danger of overheating of the brake shoes and wheel tyres (which may be a serious menace with mechanical brakes) is eliminated, thereby conducing to greater safety in operation and more uniform braking. Further, higher operating speeds on the gradients become possible and heavier trains can be taken down the gradients.

In these circumstances regenerative braking results in a considerable reduction in the operating costs compared with mechanical braking.

Practical results. The Giovi-Genoa lines of the Italian State Railways† form a striking example of the advantages of electric regenerative braking on a railway with heavy gradients. With electric traction the capacity of the lines has been trebled, due to the heavier trains which can be run on the down gradients and the higher speeds permissible with electric braking. The running costs have been found to be only about 75 per cent of those when the lines were operated with steam locomotives, although the plant of the generating station is not fully utilized. These low costs are the result of electric recuperation of energy on the down gradients, the recuperated energy being of the order of from 60 per cent to 80 per cent of the energy consumption for the up journey with the same train.‡ Considerable saving is also effected in the brake shoes, wheel tyres, and rails, as the mechanical brakes are only used for "slow-downs" and stops.

Tests‖ on the Midi Railway (France), with a single-phase locomotive and a 280-ton train on a gradient of 1 in 59 (1·7 per cent), showed that, at a speed of 23·6 ml.p.h., 400 kW. (at a power-factor of 0·83) was returned to the supply system. This power corresponds to approximately 40 per cent of that required by the train in ascending the gradient at the same speed. With a lighter train—weighing 100 tons—the power-factor during recuperation was nearly unity.

General conditions relating to electric regenerative braking on main-line and mountain railways. In the application of any system of electric

* Generally, regenerative braking is desirable, and necessary, in any electrification scheme for lines having long gradients exceeding 0·6 per cent (1 in 166).

† For a description of this electrification see *Tramway and Railway World*, vol. 27, p. 345; vol. 35, p. 184.

‡ In all cases of regenerative control the efficiency of the equipment has an important bearing on the economical results. It is only with the use of large gearless three-phase motors that results of the above order can be obtained.

‖ See *The Engineer*, vol. 115, p. 174. These tests were carried out (in 1912) when the line was first electrified, the single-phase system being then in use.

regenerative braking to these railways three important conditions have to be fulfilled, viz.—

(1) The speed-torque characteristics of the regenerative equipment must be such that mechanical stability is obtained over the whole range of operating speeds, i.e. an increase in speed must be accompanied by an increase in the braking torque.

(2) The electrical or volt-ampere characteristics of the equipment must ensure electrical stability over the whole range of operating speeds, i.e. sudden fluctuations in the line voltage must not cause flash-overs or sudden fluctuations in the braking torque.

(3) If and when the recuperated energy exceeds the energy demand of other trains operating on a given section of the distributing system, the substation converting plant must be capable of returning the excess energy to the primary supply system, and the latter must be capable of absorbing this energy. Hence, in the case of railways which are supplied from a separate generating station which has no other load, provision must be made for dissipating any excess energy in loading rheostats (which are usually of the water type); otherwise dangerous operating conditions, both at the generating station and at the trains descending gradients, would occur.

Electric Regenerative Braking Systems

I. **Regenerative braking with three-phase motors.** This is the simplest system of regenerative braking, especially when automatic liquid rheostats are employed. No additional apparatus or equipment is necessary, and no extra notches or special operating positions are required on the master controller.

The essential feature in the control of the three-phase induction motor for regenerative braking depends upon the property of this machine to operate as a non-synchronous (induction) generator when driven at speeds above synchronism. The machine, however, is not self-exciting as a generator and must be connected to a system supplied by synchronous generators; this system supplying the excitation and determining the frequency at which the induction generator operates.

The relationship between torque and slip for generator operation is similar to that for motor operation (except for a slight difference in the magnitudes of the maximum torque in the two cases), i.e. the slip (which is negative*) with constant resistance in the rotor circuit is approximately proportional to the torque, while for constant torque the slip is approximately proportional to the resistance of the rotor circuit.

Fig. 219 shows typical torque-speed curves for both motor and generator operation. Observe that with no external resistance in the rotor circuit the speed varies only very slightly over the whole range of the torque, and that the effect of adding external resistance to the rotor circuit is to increase the speed for a given braking torque. Hence, when braking with zero external resistance in the rotor circuit the speed will be practically unaffected by the steepness of the gradient, and will also be practically independent of the load, i.e. weight of the train. But if increased speeds are necessary with light loads they may be obtained by

* Thus if n = speed of rotor in r.p.m., n_s = synchronous speed in r.p.m., the slip $= (n_s - n)/n_s = -(n/n_s - 1)$.

inserting resistance in the rotor circuit. Alternatively, multi-speed motors or cascade control may be employed.

The curves of Fig. 219 show also that the maximum braking torque available from the machine is greater than the maximum motoring torque. The former is usually of the order of three times the continuous-load torque, and is always considerably above the torque necessary to slip the driving wheels.

Regenerative braking on level track can be obtained only with multi-speed equipments. Thus with the two-speed cascade system, regenerative

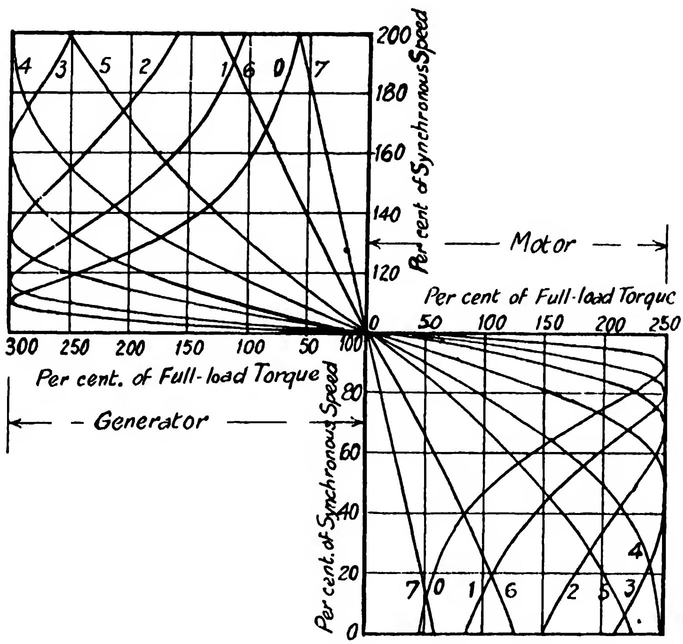


FIG. 219. - Speed-torque Curves for Motor and Generator Operation of Polyphase Induction Machine.

braking is obtained at speeds above the cascade-synchronous speed by cascading the motors, the control of the braking retardation being effected by regulating the resistance in the rotor circuit of the secondary motor. Hence, with this (two-speed) equipment, the economy obtained from regenerative braking on level track will be small. Even a four-speed equipment will not show marked economy on account of the unavoidable losses in the rheostats.

Regenerative braking on gradients, however, will show considerable economy, as the machines can be operated without external resistance in the rotor circuit, i.e. under conditions of high efficiency. The energy returned to the distribution system is equal to the work done by gravity on the descending train, less the energy expended against train-resistance and the losses in the motors. Thus the output from the machines (which is practically proportional to the braking torque) is determined by the weight of the train and the gradient. The speed—with zero external

resistance in the rotor circuit—is determined by the speed-combination of the machines, and will be slightly higher than that corresponding to the motor speed for this combination. In general, therefore, the speed-combination which is used when ascending a given gradient will also be used when descending this gradient. But in the latter the train weight which can be handled by a given locomotive is greater than that in the former case.

When two or more locomotives have to be coupled together for the purpose of handling a heavy train down a gradient, it is desirable that the locomotives should share the load equally in spite of any differences in the diameters of the driving wheels. This condition is easily obtained with equipments provided with automatic liquid rheostats. The rheostats on the locomotive with the largest driving wheels are short-circuited, while the rheostats on the other locomotives are adjusted (from the driving master controller) to maintain a load on these locomotives equal to that on the former locomotive.

II. **Regenerative braking with direct-current motors.** In this case the voltage generated in the armatures when braking must exceed the supply voltage by an amount which is equal to the voltage drop (due to resistance) in the machines and connections. Moreover, the generated voltage must be maintained at this value independent of the speed and braking torque. These conditions necessitate either shunt- or separately-excited field windings.

The speed and braking torque are controlled by regulating the excitation. They could also be controlled by a variable resistance, or, alternatively, a booster, connected in the armature (main) circuit. But the series-resistance method is inefficient and unsuitable for practical purposes, and the booster method, although practicable, involves additional machines and control gear.

The range of speed and braking torque obtainable from a given equipment with this method of control (i.e. by regulating the excitation of the traction motors) is governed by considerations of heating and commutation. For example, the torque corresponding to a given combination of the motors is limited, at the lower speeds, by the heating of the armature and field windings. At the higher speeds (i.e. when the machines are operating with weakened fields) the torque is limited by commutation. Thus, to obtain satisfactory commutation the ratio of field ampere-turns to armature ampere-turns must always exceed a minimum value (which is of the order of 0·4).

Regenerative braking with shunt machines cannot be effected with the simplicity which this method of excitation would suggest, as difficulties are encountered in the series-parallel operation of the machines, both as generators and motors. Moreover, shunt machines are inherently sensitive to voltage fluctuation and would be extremely unstable on a traction circuit. In the past a large amount of development has been expended in the application of shunt and compound machines to regenerative braking under tramway conditions, but such equipments had ultimately to be abandoned owing to operating difficulties connected with both the car equipments and the generating station.

Modern developments in regenerative braking on direct-current railways,

therefore, have been entirely with standard series traction motors. Suitable characteristics for regenerative braking are obtained by separately exciting the field windings,* and electrical stability is obtained either by differentially compounding the exciter or by connecting the exciting circuit in parallel with a resistance inserted in the main circuit. The braking torque is controlled either by regulating the excitation of the exciter or by inserting a booster in the main circuit. The booster exciter possesses certain advantages over the single exciter for motor-coach trains, as the booster may be utilized for starting and speed control. On the other hand the single exciter is desirable for locomotive equipments on

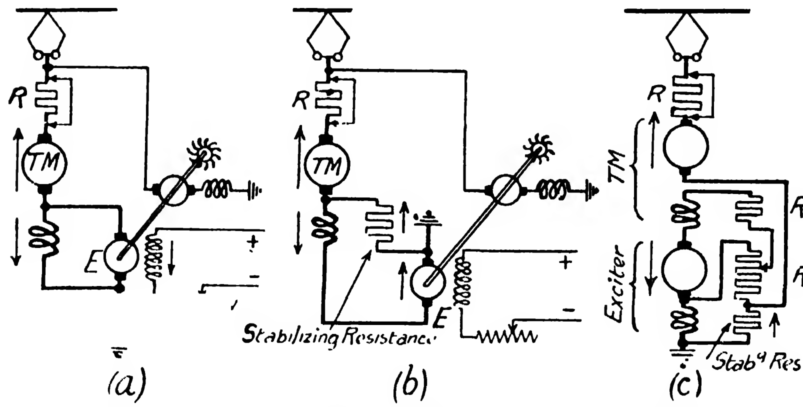


FIG 220.—Elementary Diagrams of Methods of obtaining Regenerative Braking with Direct-current Motors.

account of the larger motors and the more severe and more varied starting conditions.

The exciter may be driven either by a separate motor (which is usually series wound and is connected to a permanent mechanical load, such as a fan or blower) or from one of the axles of the locomotive. In the latter case the exciter is usually an axle-mounted generator and is driven from one of the trailing axles. In some cases—e.g. with locomotive equipments having a large number (six or more) of motors—one of the driving motors is used as an exciter.

Elementary diagrams of connections for these cases are given in Fig. 220. In diagram (*a*) the exciter is differentially compounded, and is driven by a series motor, to which is also connected a permanent mechanical load. The shunt field winding of the exciter is separately excited from an auxiliary supply: the differential series winding is connected in the main circuit and carries the recuperated current. The exciter armature has to carry the sum of the armature and field currents of the traction motors. Control of the braking torque is effected by a rheostat connected in the shunt-field circuit of the exciter.

Diagram (*b*) also refers to a motor-driven exciter, but in this case the exciting circuit (i.e. the exciter armature together with the field

* The term "field windings" here refers to exciting windings and does not include the commutating-pole windings.

winding of the traction motor) is connected in parallel with a "stabilizing" resistance in the main circuit. The exciter is virtually a shunt machine separately excited from an auxiliary source. The exciter armature carries only the exciting current of the traction motor, but its voltage must be equal to the sum of the voltage drops in the stabilizing resistance and the traction motor field winding. The same scheme of connections may be employed with an axle-driven exciter.

Diagram (c) shows a method of utilizing one of the traction motors as an exciter. In this case the "exciter" operates as a self-excited series generator, and supplies not only its own excitation but also that of the

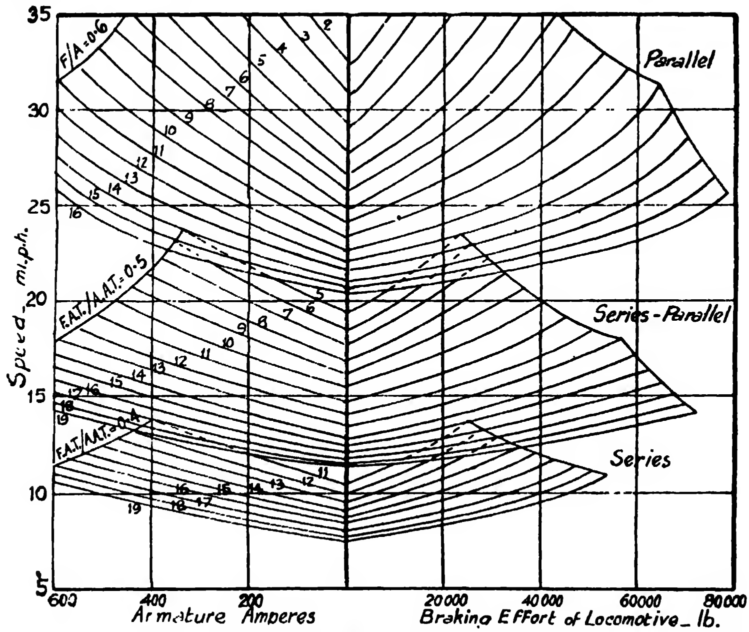


FIG. 221. Speed-current and Speed Tractive-effort Curves for Electric Locomotive when Braking Regeneratively. Motor-driven exciter and 0·04 ohm stabilizing resistance.

other machines which are generating. Control of the excitation and braking torque is obtained by both shunting the field winding of the "exciter" and varying the resistance in the exciter-armature circuit.

The speed-torque characteristics obtained from each of these methods have the same general form, but, for given conditions, the variation of speed with torque is generally smaller with a stabilizing resistance than with a differentially compounded exciter. Typical characteristics are shown in Fig. 221. Such characteristics can be calculated when the requisite data are available, but the calculations are more tedious than those for the motor speed-torque characteristics, as the shape of the magnetization curve of the exciter and armature reaction have to be taken into account.

It is important to observe that for each value of excitation the torque increases as the speed increases until a definite torque is reached, after

which an increase of speed results in a decrease of torque (i.e. the braking system becomes unstable mechanically). The value of the maximum torque depends upon the excitation, the largest value being obtained with the largest excitation.

Comparison of above methods. With the differentially-compounded exciter method (Fig. 220(*a*)) the traction motors must first be connected to the line as motors when regenerative braking is required, the change from motoring to braking being effected by increasing the excitation. Stability against surges of current due to sudden fluctuations of line voltage is obtained by the differential compounding of the exciter in combination with armature reaction and voltage drop in the exciter armature. For example, should a sudden decrease in the line voltage occur, the tendency for the recuperated current to increase is checked by a reduction of the exciter voltage, which decreases the excitation of the traction motors.

With the motor-driven exciter method employing a stabilizing resistance the traction motors may be connected to the line as generators, and, on account of the inherent stability of this method, the voltage of the machines at the time of their connection to the line does not require exact adjustment. In the event of a sudden decrease in the line voltage the tendency for the recuperated current to increase is checked by the decreased excitation due to the increased voltage drop across the stabilizing resistance.

This method possesses the advantages of greater simplicity and a smaller exciter for a given motor equipment than the preceding method, and the losses in the stabilizing resistance are to some extent balanced by the decreased commutator losses of the exciter and the maintenance of this machine.

With the traction-motor exciter method shown in Fig. 220 (*c*), the "exciter" carries only the field current of the traction motors. The stabilizing resistance carries the sum of the armature and field currents. Electrical stability is therefore obtained by a method similar to that employed in Fig. 220 (*b*). The control of the excitation of the exciter and the traction motors is effected by utilizing a portion of the main starting rheostats and contactors. Hence, regenerative braking entails very little additional equipment. On the other hand, the range of speeds over which braking is possible is less than that obtainable with the preceding methods (with which two or more combinations of the motors are possible).

A comparison of the braking characteristics for the motor-driven exciter and traction-motor exciter methods applied to a particular case is given in Fig. 222. These curves* show the calculated performances for a 77-ton, 3000-volt locomotive equipped with six 1000-volt motors. With the motor-driven exciter two combinations of the traction motors are available for braking, but with the traction-motor exciter only one combination is available. Moreover, the total braking effect for given conditions is greater in the former case than in the latter case, as the whole of the traction motors are operated regeneratively.

* Obtained from data given in a paper on "Regenerative braking for direct-current locomotives," by A. Bredenberg, Jnr. *Proceedings of American Institute of Electrical Engineers*, xlv, 613.

The comparison of the two methods, in so far as traffic operation is concerned, may be summarized briefly thus—

With a motor-driven exciter and limiting conditions of armature and field currents in the traction motors, a heavier train may be taken down a given gradient than could be hauled up this gradient, the speed during descent being higher than that of ascent.

On the other hand, with traction-motor excitation the maximum train weight which can be taken down a given gradient is practically equal to that which can be hauled up this gradient, the speed of descent being slightly higher than that of ascent. The difference in the ascending

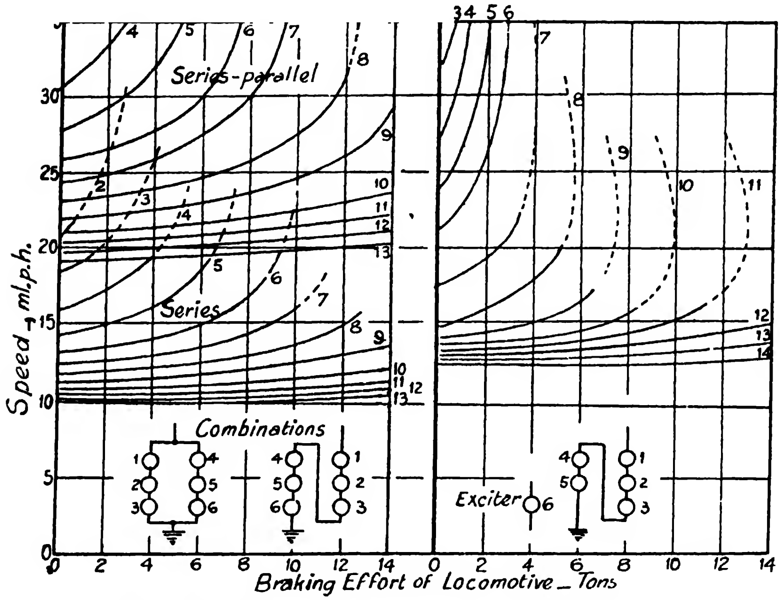


FIG. 222.—Speed Tractive-effort Curves for Electric Locomotive when Braking Regeneratively.

and descending speeds is small for light gradients, but becomes greater as the gradient increases.

Traction-motor excitation is, therefore, preferable for relatively light gradients (not exceeding about 1 in 70) or for short heavy gradients. Motor-exciter excitation is preferable for long and heavy gradients.

For locomotive equipments in which more than two combinations of the motors are possible, the traction-motor exciter method may be unsuitable on account of the limited speed range available. Under certain conditions, however, it may be possible to increase the range by employing two combinations (e.g. with a 3000-volt locomotive equipped with six 1500-volt motors two combinations can be obtained), but the speed range will always be less than that of the motor-exciter method.

Control equipment. The additional equipment necessary for regenerative braking will depend upon the method employed. In all cases a change-over switch (which may be of either the drum or the contactor

type) is necessary for changing over the connections from motoring to braking. A separate master controller or a special master controller with three operating handles and contact drums is also necessary for controlling the speed and braking effect. Protective relays are also necessary.

With traction-motor excitation very little equipment, in addition to that mentioned above, is necessary if the main starting rheostats and contactors are utilized. Some additional rheostats and contactors, however, may be necessary.

With a motor- or axle-driven exciter a suitable field rheostat, together with a group of contactors or a drum-type controller, is necessary for regulating the excitation, and with a motor-driven exciter starting apparatus is necessary for the motor.

Example of control equipment for regenerative braking. This example refers to a 3000-volt, 1200-h.p. locomotive with Metropolitan-Vickers equipment. The control equipment for motor operation is arranged on the series-parallel system and is described in Chapter IX (p. 249). For regenerative braking a motor-driven exciter with stabilizing resistance is employed, and both combinations of the motors can be used if desired. Transition is effected by opening the main circuit.

Simplified diagrams of the motor and control circuits—in so far as regenerative operation is concerned—are given in Fig. 223. The exciter is driven by a double-armature, 3000-volt motor which is mechanically connected to a blower. The motor has a series winding (which normally supplies the majority of the excitation) and a light shunt winding which is separately excited from an auxiliary source (100 volts). The exciter has a main shunt winding, which is separately excited, and a light series (cumulative) winding which is connected in series with the motor. The object of this (series) winding is to compensate for gradual or semi-permanent fluctuations in the line voltage. Thus if the line voltage increases, the speed of, and the current input to, the motor both increase. Hence the voltage generated in the exciter increases, thereby increasing the excitation of the traction motors. A decrease in the line voltage produces the opposite effect.

The change of connections from motoring to braking (which involves the cutting-in of the exciter and stabilizing resistances) is effected by a cam-operated group of contactors (Fig. 172).

The control operations are—

The combined reversing and motor-combination handle of the master controller (Fig. 175) is placed in the "forward-series" position, the braking handle is moved to the first notch, and the accelerating handle is moved to the first notch. The last operation establishes the power (regenerative) circuit, the motors being in series with each other and in series with the starting rheostats.

The braking handle is then adjusted until the ammeter shows that recuperation has commenced. The current is maintained approximately constant at a small value by manipulating the braking handle, while the starting rheostats are cut out, after which operation the braking current is adjusted to the desired value by manipulation of the braking handle (which controls the amount of resistance in the shunt field of the exciter).

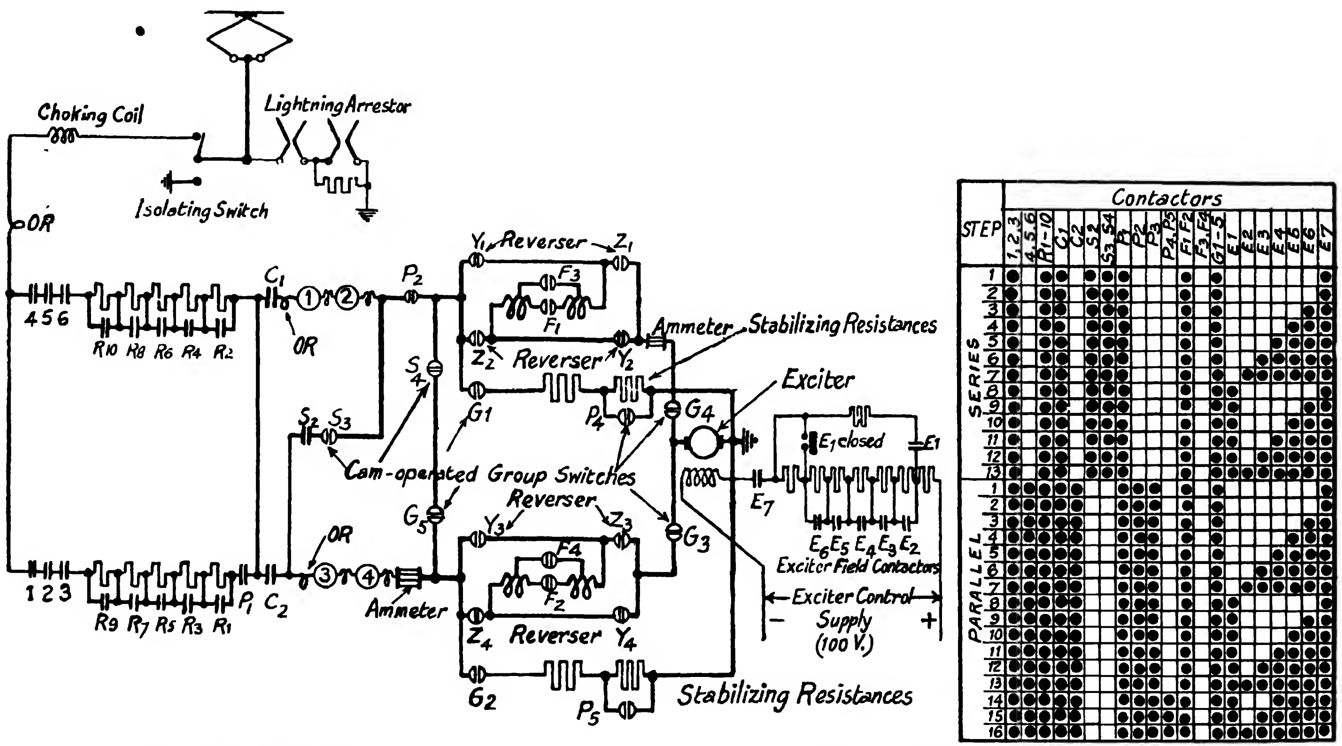


FIG. 223.—Main-circuit Connections for Regenerative Braking with Series-parallel Locomotive Equipment (Metropolitan-Vickers.)

Similar operations are necessary when braking is desired with the parallel combination of the motors, but in this case the combined reversing and motor-combination handle of the master controller is placed in the "forward-parallel" position.

III. **Regenerative braking with single-phase motors.** The problem of obtaining regenerative braking from single-phase series motors presents difficulties which are considerably greater than those discussed above in connection with direct-current equipments. In fact these difficulties are of such magnitude in some cases that rheostatic braking—which can be obtained by operating the motors as self-excited series generators and loading them on rheostats—is often resorted to on mountain railways. In other cases the split-phase system is adopted.

The chief difficulties are concerned with (1) the prevention of the machine building-up as a direct-current generator, and (2) the attainment of a high power factor during recuperation. Of these, the second involves

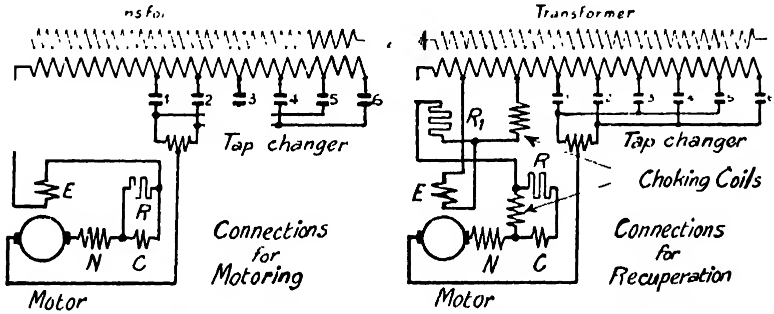


FIG. 224.—Single-phase Connections for Motoring and Regenerative Braking.

greater attention than the first (which can be overcome successfully by isolating the armature and field circuits and separately exciting the latter). When the difficulty of obtaining a high power factor is overcome, the control of the speed and torque during regeneration is, relatively, a simple matter, and can be effected by the same apparatus (e.g. the tap-changer) as is employed for controlling these quantities when the machine is operating as a motor. In this respect the control of the single-phase motor during regenerative braking is more flexible than that of the direct-current motor, as the torque obtainable at high speeds is not limited by considerations of commutation. Moreover, regeneration over a wide range of speeds can be obtained with practically constant excitation, and, therefore, minimum root-mean-square currents in the armature and field windings.

The conditions necessary to obtain a high power factor during regeneration are, briefly—

The E.M.F. generated in the armature must be practically in phase-opposition with the "supply" voltage (i.e. the voltage across the terminals of the portion of the transformer secondary winding to which the armature is connected). Hence the flux and exciting current must be practically in phase with the supply voltage, and therefore, as series

excitation is inadmissible, the voltage impressed on the separately excited field (exciting) winding must have a phase difference of practically 90° with respect to the supply voltage.

A number of schemes are possible for obtaining the correct phase and magnitude of the exciting current. Some of these involve the use of auxiliary machines and others the use of auxiliary stationary apparatus.

A simple scheme, due to Messrs. Siemens-Schuckert, is shown diagrammatically in Fig. 224. This scheme involves only the use of auxiliary choking coils and a fixed resistance. The excitation winding of the motor is separately excited from a section of the transformer winding, and the correct phase of the exciting current is obtained by means of a suitably adjusted choking coil and resistance connected as shown. No means are provided for regulating the excitation. The armature is connected in series with the compensating and commutating-pole windings, and the combination is connected to tappings on the transformer, a group of contactors and a preventive coil being employed for tap changing. In order to obtain the correct phase for the commutating flux under generator conditions, the resistance, which shunts the commutating-pole winding when the machine operates as a motor, is connected in series with this winding and both are shunted by a choking coil.

The machine, therefore, possesses a "shunt" characteristic when operating regeneratively, and its speed, for a given tapping-voltage, is sensibly constant. Regulation of speed is, of course, effected by varying the tapping to which the armature circuit is connected.

If the braking torque is removed—due to either a decrease in the gradient with a constant tapping-voltage applied to the armature circuit, or an increase in the voltage applied to the armature circuit with a constant gradient—the machine runs as a shunt motor at a slightly lower speed but with a bad power factor. Hence at the completion of the braking period the connections must be changed over to give normal operation as a series motor.

The method possesses the advantages of simplicity, security (i.e. good mechanical stability), a favourable power-factor during recuperation, and low additional weight (which is of the order of 4 per cent of the weight of the electrical equipment of the locomotive), cost, and maintenance.

These advantages tend to balance the disadvantage of a reduction in efficiency (with generator operation) due to the losses in resistances and choking coils.

With single-phase equipments it is generally impossible to obtain very high values (such as are common to three-phase equipments) for the ratio of the power recuperated down a gradient to the power required for ascending the gradient under similar conditions, as the overall efficiency of single-phase equipments is considerably lower than that of three-phase equipments. Hence, where recuperation is of importance on a single-phase system, the results obtained with an equipment consisting of three-phase motors and a phase converter will generally be superior to those obtained with a straight single-phase equipment.

CHAPTER XIII

AUXILIARY ELECTRICAL EQUIPMENT FOR TRAMCARS AND TROLLEY-BUSES

THE electrical equipment of a tramcar or a trolley-bus includes, in addition to the motors and controllers, (1) a current collector (e.g. a "trolley" or a "plough"), by means of which the current is conveyed from the overhead lines or conductor rails to the controller and motors; (2) rheostats for starting and regulating the speed of the motors; (3) protective apparatus to protect the equipment against overload and, in the case of overhead systems, against lightning discharges; (4) the necessary cables for the "power" circuits; (5) a lighting, and, in some cases, a heating installation.

Trolley collector. This consists of a standard or base, a trolley-pole, and a trolley-head. The trolley-head is fixed to the end of the trolley-pole, from which it is insulated, and carries the trolley wheel.

The trolley-head may be of either the fixed or swivelling types. The former is intended for trolley wires arranged centrally with the track, and the latter is suitable for operating on trolley wires displaced from the centre of the track. Views of typical trolley-heads are given in Fig. 225, and the various parts are shown in Fig. 226.

The trolley-wheel is usually made of gun-metal having a high percentage of copper, but in some cases a composite wheel—with a copper centre and pressed steel flanges—is used. The diameter at the bottom of the groove is usually 3 in., but for high speeds a larger diameter (about 5 in.) is adopted. The wheel may be fitted either with a self-lubricating hollow steel spindle or with a solid steel spindle and a graphite bush. The guard or shield (which protects the edges of the trolley-wheel) is, in the swivelling type, mounted on a vertical spindle and is fitted either with a ball bearing or a plain bearing with a lubricated "friction washer." These details can be observed in Fig. 226.

The trolley-pole is a light steel tube about 15 ft. long, 1 in. in diameter at the head end, and 1½ or 2 in. in diameter at the butt end. Rubber sleeves are fitted at each end to insulate the pole from the trolley-head and the standard.

Trolley standards are of two types, (1) vertical, (2) dwarf. The former is intended for open double-deck cars, and the latter for single-deck cars and covered double-deck cars.

A section of a **vertical standard** is shown in Fig. 227. The outer steel tube *B* is fixed into a cast-iron base *A*, and supports, on ball bearings, the cast-iron head *C*, to which is fixed the internal tube *D*. This tube extends the whole length of the outer tube to a guide bearing *E* in the base *A*. The trolley-pole is fixed to a hooded pole-holder *F*, which is hinged to the head of the standard at *G*. A pin *H* is located in the inner portion of the hood, and carries the tension-rod *J*. The upper end of this rod is formed into a square head, while the lower portion is threaded to engage the nut *K*, which is in the form of a cross-bar and is seated in slots in the

casting *L*, the latter being free to move in the tube *D*. A collar *M* is riveted to the inner tube near its upper end, and between this collar and the casting *L* is placed the spring *N*. An adjustable stop *O*, fixed in the head *C*, prevents the trolley-pole from rising above a certain elevation.

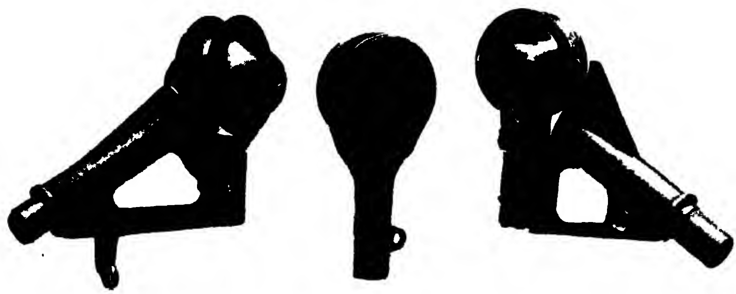


FIG. 225. Types of Trolley-heads: I, swivelling head with ball bearing; II, fixed head or "harp"; III, swivelling head with "friction washer."

The spring is, therefore, in compression, and that its leverage on the pole-holder is a minimum in the lowest position of the trolley-head. As the trolley-pole becomes inclined, its effective leverage decreases; the tension in the rod *J* decreases, and its leverage increases. Thus, slight

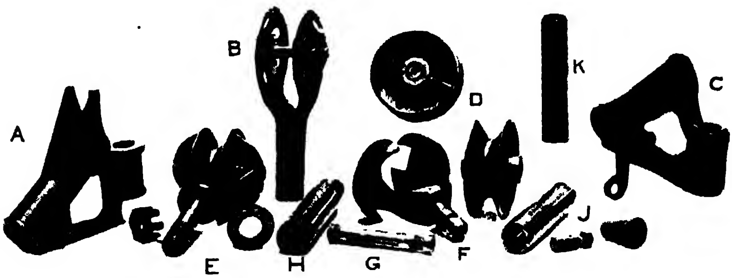


FIG. 226. Parts of the Trolley-heads illustrated in Fig. 225. *A*, body for head III; *B*, body for head II; *C*, body for head I; *D*, trolley wheel with graphite bush; *E*, shield for "friction-washer" type of head; *F*, shield for ball-bearing head; *G*, hollow self-lubricating spindle; *J*, terminal sleeve with cable terminal and insulating bush; *K*, rubber sleeve (for insulating terminal sleeve from trolley pole); *H*, terminal sleeve completely assembled.

deviations of the trolley-pole from the normal operating position do not affect the pressure on the trolley-wire, but under low bridges the pressure will be reduced, thereby avoiding excessive wear on the wire at these places. The variation of pressure is shown in Fig. 228.

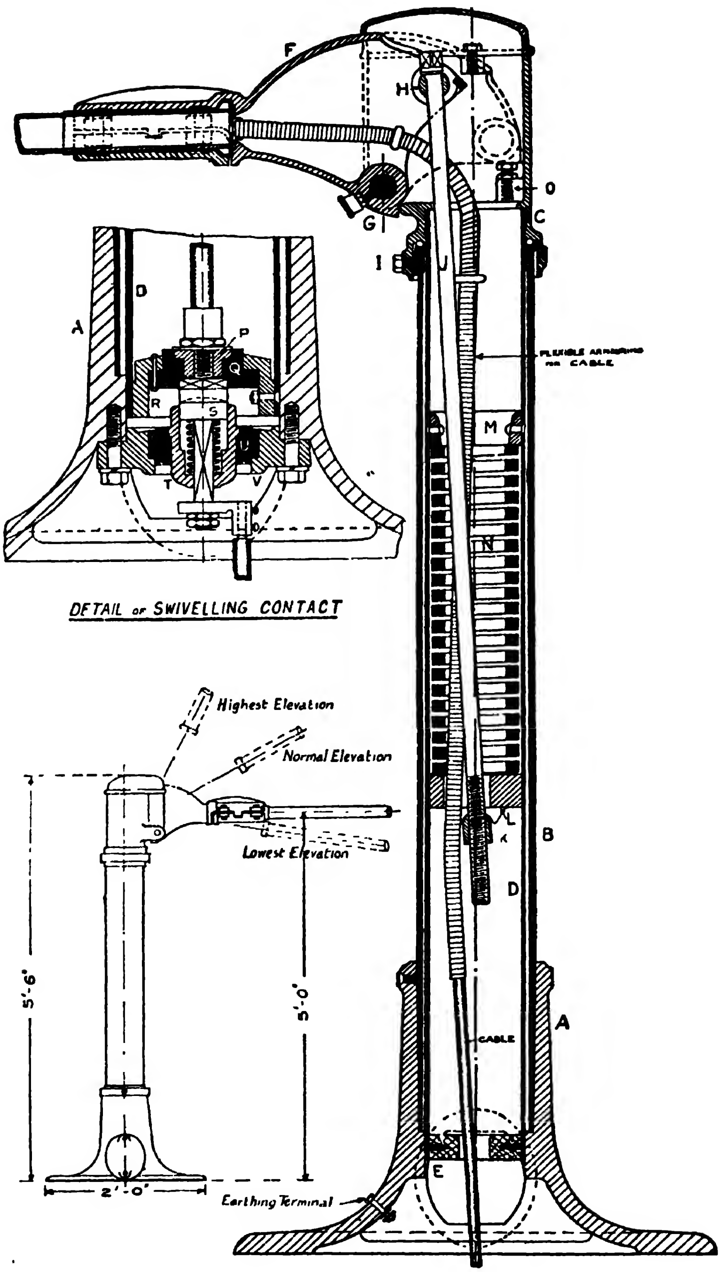


FIG. 227.—Section of Trolley Standard for Double-deck Cars without Top Covers (Brecknell, Munro & Rogers).

The horizontal movement of the trolley-pole is restricted, by the stop *I*, to less than a complete revolution. A swivelling contact, however, allows unrestricted horizontal movement of the trolley-pole. Details of such a contact are shown in Fig. 227. The cable from the trolley-head terminates in a contact *P*, which is fixed to a bush of insulating material

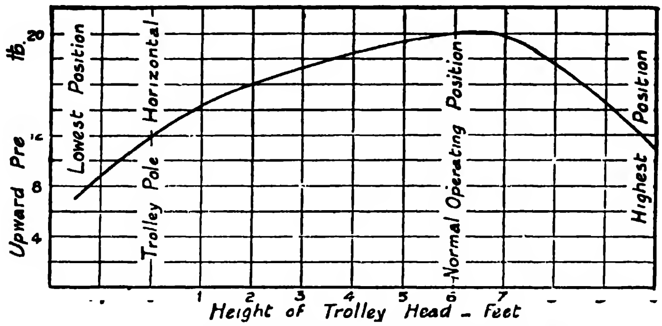


FIG. 228.—Variation of Pressure on Trolley-wire with Height of Trolley-head. (Distance between centre of trolley-head and centre of standard, with trolley-pole horizontal, 14 ft. 6 in.).

Q, carried in a cup-shaped casting *R* attached to the lower end of the inner tube *D*. The lower contact *S* works in a guide *T*, which is fixed in an insulating bush *U*, the latter being fixed in a casting *V* bolted to the base of the standard. This contact (*S*) is pressed against the upper contact (*P*) by means of a spring, and a square is formed on the neck of the

FIG. 229.—Dwarf Trolley Standard (Brecknell, Munro, & Rogers).

lower contact to prevent rotation of the cable terminal to which the cable leading to the controller is attached.

The standard is usually earthed through two 250-volt lamps connected in series.

A typical **dwarf standard** for covered double-deck cars is shown in Fig. 229. This standard can be made with a total height, when the trolley-pole is horizontal, of only $3\frac{1}{2}$ in. The head of the standard is carried on a central sleeve, forming part of the base, and is provided with ball

bearings, while a stop is fitted, as in a vertical standard, when the base is not furnished with a swivelling contact. The arrangement of the springs, tension-rods, and pole-holder is shown clearly in the illustration.

The **current-collector for a trolley-bus** is usually of the double-trolley type, and consists of separate trolley heads and poles fitted to a special dwarf standard. This standard consists of two dwarf standards, of the

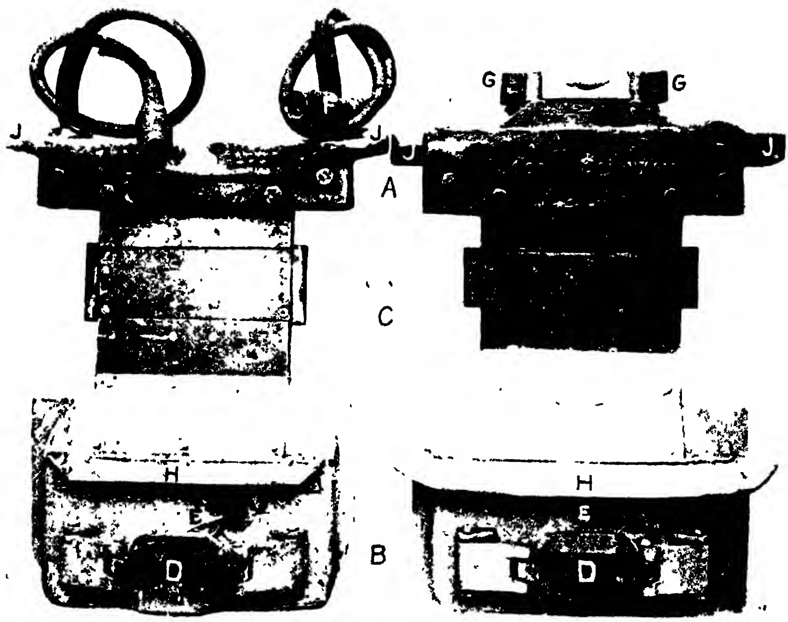


FIG. 230. - Plough Collectors (London County Council Conduit Tramways). The plough shown on the right has been developed for cars running on combined conduit and overhead trolley systems.

type shown in Fig. 229, arranged one above the other as shown in (Fig. 270). In some cases (Fig. 269) single dwarf standards arranged side by side are employed.

Plough collector. Typical ploughs for conduit tramways are shown in Fig. 230. The head *A* is of cast steel, the lower portion *B* is of wood, while the intermediate portion *C* (which passes through the slot of the conduit) is built up of steel plates. The shoes *D*, which make contact with the conductor rails (see Chapter XXI), are of cast iron, and are pressed outwards by semi-elliptic springs. Each shoe is connected to a terminal, fixed in the base of the plough, by a flexible copper connection *E*, which acts as a fuse in the event of a short circuit within the plough. The connections between the shoe terminals and the cables *F* (or contacts *G*) at the head of the plough are in the form of copper strip, in order that they may be carried between the steel plates in the intermediate portion of the plough, the overall thickness of which is only ½ in.

The lower portion of the plough is protected from mud, etc., by a hood *H*. The head of the plough is fitted with projections *J*, which slide in the plough carrier on the truck.

For cars which have to operate on both conduit and overhead trolley systems, the London County Council Tramways have developed a plough which can easily be removed from the car.* In this plough the head is

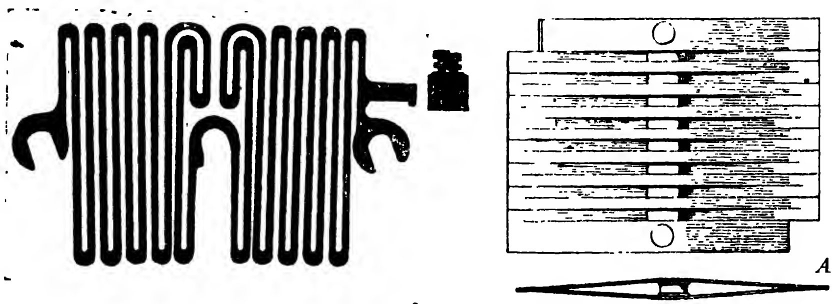


FIG. 231.—Resistance Grids.
Left—Cast grid (B.T.-H. Co.) *Right*—Pressed splayed grid with spacer in position (Rheostatic Co.).

fitted with spring contact-shoes *G*, instead of cables, and these shoes make contact with two insulated bus-bars fitted to the plough carrier. Before this device was adopted it was necessary, when changing from the conduit to the trolley system, and vice versa, to disconnect and connect the cable connectors under the car. The bus-bars are connected

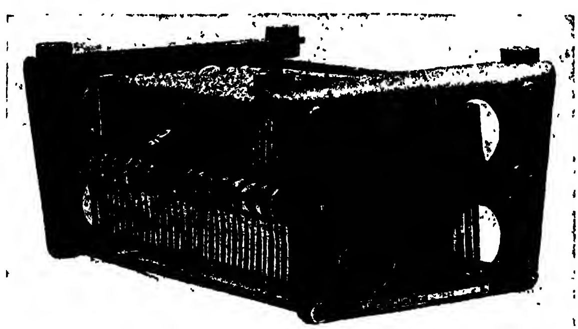


FIG. 232.—B.T.-H. Tramcar Rheostat (for location under car).

to a change-over switch, from which connections are taken to the controllers and the trolley. In one position of the switch the bus-bars are connected to the controllers and the trolley circuit is isolated, while in the other position the trolley is connected to the controllers and the bus-bars are isolated.

Rheostats. The grid rheostat with mica insulation is adopted in all modern equipments. This type of rheostat consists of a number of

* For details of the method of removing and replacing the plough, see p. 551.

resistance grids supported on mica-insulated rods and clamped between mica and steel washers. The supporting rods are usually mounted in either pressed-steel or cast-iron end frames for location under the car, but in some cases they are mounted in a ventilated cast-iron box for location on the platform under the staircase.

Two types of grids are in use, (1) cast, (2) malleable (unbreakable).

Cast grids consist of either a special grade of cast iron or an alloy of aluminium and cast iron, and are treated with a rust-preventing compound. A typical grid is shown in Fig. 231, and a rheostat is shown in

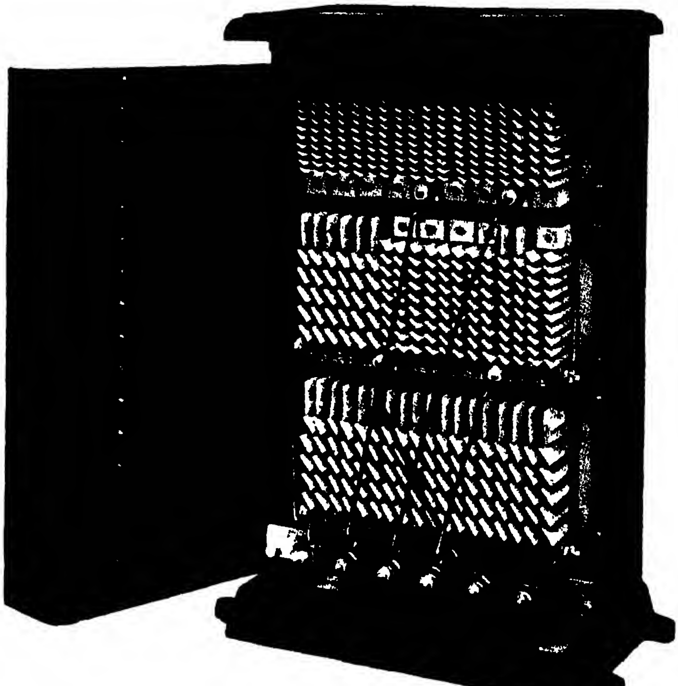


FIG. 233.—Tramcar Rheostat (Platform Type) with Unbreakable Pressed Splayed Grids.
(Rheostatic Co.)

Fig. 232. Each grid has three slotted bosses and a projecting lug to which a terminal may be attached. The bosses are thicker than the other portions of the grid and are ground flat; they form not only the means of support but also the electrical connection between adjacent grids. Series connections are effected by inserting a thin mica washer between alternate outside bosses and a similar washer between all the middle bosses.

Malleable grids consist of rustless resistance wire of rectangular cross-section. The grids are formed by bending a continuous length of this wire in a series of narrow loops—similar to those of cast grids—larger loops being provided at the ends and centre for supporting the grids on mica-insulated rods. The wire is continuous (in the form of a loop) from

grid to grid (except where a change in cross-section is necessary) and cable terminals may be clamped to any of these end loops.

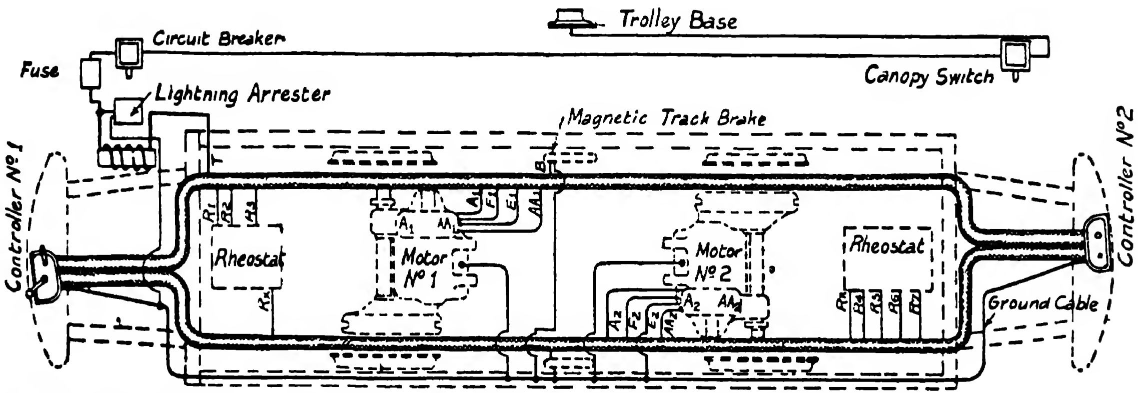
Alternatively, malleable grids may be pressed from sheet metal, but to obtain rigidity the splayed form of grid (due to the Rheostatic Co.) must be employed. The grids are formed by slitting the metal sheet and splaying the strips in the manner indicated in Fig. 231. Hence no waste material is formed during manufacture. The ends of the "loops" are twisted as shown in Fig. 233, to provide the necessary separation. After pressing, and before assembly, the grids are sheradized (i.e. the surface is

Fig. 234. -Tramcar Circuit-breakers.
Left—B.T.H. *Right*—Metropolitan-Vickers.

alloyed with zinc). The grids are supported on mica-insulated steel rods and the extreme ends of each grid are bent in opposite directions, at right angles to the axis of the grid, as indicated at *A*, Fig. 231. The grids are spaced by pressed metal spacers and mica plates, which extend between the supporting rods and pass through the splayed "loops," thereby giving these a rigid support. The bent-up portions (*A*, Fig. 231) of adjacent grids are electrically spot welded and form tapping points for the external connections (Fig. 233).

A tramcar rheostat constructed of these grids is shown in Fig. 233. The grids are built into a frame, of either cast-iron or pressed steel, which is fitted with louvred covers and is intended for occupying a position on the platform under the staircase. The location of the rheostat on the platform is preferable to the under-car position, as the rheostat is protected from dust and mud.

Protective devices. (1) *Circuit breaker.* The equipment is protected against excessive overloads by an automatic circuit breaker, which is



NB. At Controller No. 1 connect cable A_2 to terminal AA_2 & cable AA_2 to terminal A_2
" " 2, " " A_1 " " AA_1 " " AA_1 " " A_1
(See Plan for location of Armature cables A_1, AA_1, A_2, AA_2)

FIG. 235.—Diagram of Wiring for Power Circuits on Tramcar.

connected between the controller and the current collector. On tramcars equipped with trolleys the circuit breaker is mounted under one of the canopies, within reach of the motorman. A switch is connected in series with the circuit breaker and fixed under the other canopy. With cars operating on the conduit system, the polarity of the conductor rails is liable to be reversed, and a double equipment of switches and circuit breakers is provided, a switch at one end being in series with a circuit breaker at the other end. The car wiring can therefore be isolated from either end of the car. With trolley buses a circuit breaker is connected in each pole. The circuit breakers are usually mounted side by side on the dash board.

A typical circuit breaker is shown in Fig. 234. The main contacts are located in an arc chute and are provided with a magnetic blow-out, the blow-out coil actuating also the tripping mechanism. The handle is arranged to trip the circuit breaker when it is moved to the "off" position. Hence the circuit breaker can be operated by hand in the same manner as a switch.

(2) *Lightning arrester.* The equipment of cars which operate from overhead trolley wires is protected against lightning and high-voltage surges by a lightning arrester and a choking coil. The choking coil is connected in the main circuit between the circuit breaker and the controller, and the lightning arrester is connected to the "line" side of the choking coil as shown in Fig. 235.

The arrester is usually of the spark-gap and resistance type. One form consists of a single spark gap (0·015 in.) in combination with a series resistance and a magnetic blow-out, the field of which is provided by a permanent magnet. Another form consists of two electrodes and a cylindrical block of specially prepared carborundum of high resistance. The carborundum block has numerous air spaces uniformly distributed throughout its mass. A discharge through the block is, therefore, split up into a large number of smaller discharges, and the high resistance of the material prevents the discharge from being maintained by the line voltage. The carborundum block is separated from the "line" electrode by a small air space.

Car wiring. *Power circuits.* With modern tramcar equipments the wiring for the power circuits consist of two multi-core cables (one along each side of the car), with distinctive colours to the separate cables. These cables interconnect the controllers, and tappings are brought out at suitable points for connection to the motors, rheostats, and brakes, as shown in Fig. 235.

With trolley-bus equipments the motors, rheostats, controller, and circuit breakers are all arranged at the forward end of the vehicle. The connections are made by flexible cables (e.g. 248/·018, 140/·01) of the cab-tyre sheathed type.

Lighting circuits. These circuits have to provide for the interior lighting of the car as well as for the lights required by traffic regulations. The circuits are supplied from the "line" side of the canopy switch and consist usually of 105-volt lamps, five lamps being connected in series. Each circuit is controlled by a separate switch, two-way switching being necessary for the "traffic" lights.

CHAPTER XIV

AUXILIARY ELECTRICAL EQUIPMENT FOR ELECTRIC LOCOMOTIVES AND MOTOR-COACHES

THE auxiliary electrical equipment required by locomotives and motor-coaches includes: (1) current collectors; (2) motors and control gear for driving (*a*) the compressors, or exhausters, for the power brakes, (*b*) the blowers for ventilating the main motors (if these are of the forced-ventilated type); (3) the pressure converter or motor-generator for supplying the lighting, control, and auxiliary circuits of high-voltage, direct-current equipments at suitable voltage.

CURRENT COLLECTORS

The type of current collector depends upon the position of the conductor from which the locomotive or motor-coach obtains its supply. With conductor-rail distribution systems the current collector consists of a cast-iron, or cast-steel, collector shoe, which is maintained in contact with the conductor rail either by its own weight or by means of a spring. With overhead distribution systems the current collector consists of a bow- or pan-shaped sliding contact (or, in some cases, a roller contact) carried on a light framework and maintained in contact with the trolley wire by means of springs.

Collector shoes. These may be divided into three types, according to the types of conductor rails (see Chapter XXIII). In this country the top-contact conductor rail is generally used, and a typical collector shoe is illustrated in Fig. 236. The contact shoe is supported by a pair of links from two castings bolted to a "shoe plate," the latter being fixed to an insulating support attached to the axle boxes or the motor frame. The links allow of vertical motion of the shoe, and the lowest position of the latter is adjustable by means of the serrations on the shoe-plate and the supporting castings. In most cases the weight of the shoe is of the order of 30 to 40 lb., which is sufficient to ensure satisfactory contact between the shoe and conductor rail. Under normal conditions a shoe of the type illustrated is capable of collecting about 2000 amperes at speeds up to 30 ml.p.h.

When the conductor rails are located outside the track rails, the collector shoes are attached to an oak beam, which is fixed to the axle-boxes, or to a part of the truck frame directly connected to the axle-boxes (e.g. the equalizer bars in an equalized bogie). In the other position of the conductor rails (i.e. between the track rails) the collector shoe is either attached to an oak block (which is bolted to a bracket fixed to the motor frame) or to an oak beam at the end of the truck, this beam being connected to longitudinal channels carried from the axle-boxes. It should be noted that, when passing round curves, the transverse movements of the shoes will be the greater the greater the distance the shoes are from the pivotal centre of the truck.

A typical **collector shoe for an under-contact conductor rail** is illustrated in Fig. 237. The contact portion or slipper E is hinged to a

bracket *D*, which is bolted to the shoe-plate *P*, and the pressure between the slipper and the conductor rail is obtained by springs. The extreme positions of the slipper are limited by stops. This type of collector shoe

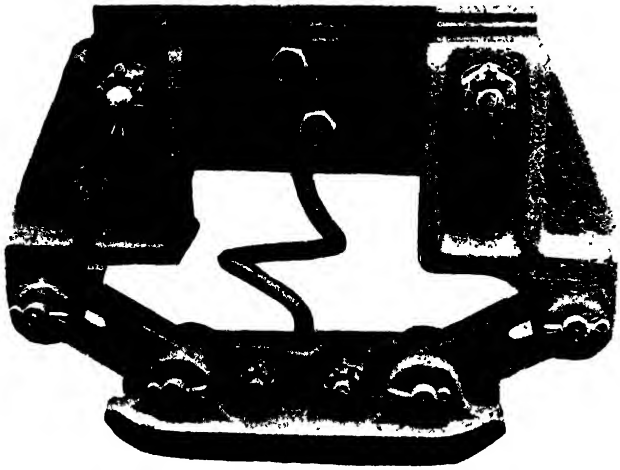


FIG. 236.—Collector Shoe for Top-contact Conductor Rails. (B.T.-H. Co.)

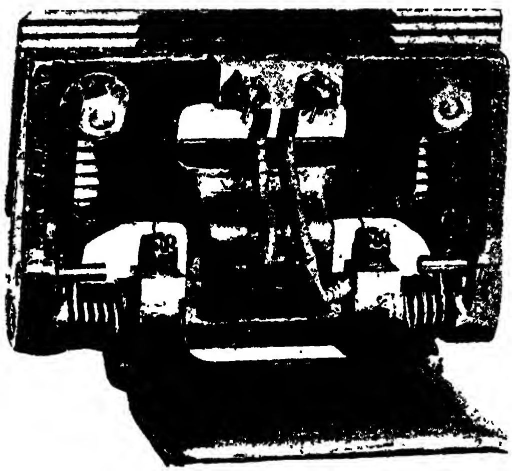


FIG. 237.—Collector Shoe for Under-contact Conductor Rails. (B.T.-H. Co.)

has also been developed for use with the top-contact type of conductor rail.

A collector shoe for a side contact conductor rail is illustrated in Fig. 238. The cast-steel contact shoe is hinged to a bracket which is bolted to a vertical serrated shoe-plate, the latter being fixed to an oak beam carried on lugs from the axle boxes. The shoe is pressed against the contact surface of the conductor rail by a spiral spring, the normal

pressure between the contact surfaces being 25 lb., and the transverse motion being limited by stops. The upper portion of the shoe is completely protected by jarrah wood, the lower edge of the protection being only $4\frac{1}{2}$ in. above the protection on the conductor rail.

Bow and pantagraph collectors. An essential condition in the collection of current from an overhead conductor is that the collector shall maintain contact with the trolley wire at all speeds. Hence the collector must follow instantaneously any irregularities in the level of the trolley wire, and therefore, with an ordinary suspension, a collector of very small inertia (e.g. a trolley wheel or a light bow) must be employed. But, although the trolley-wheel collector* is used (on account of its cheapness)

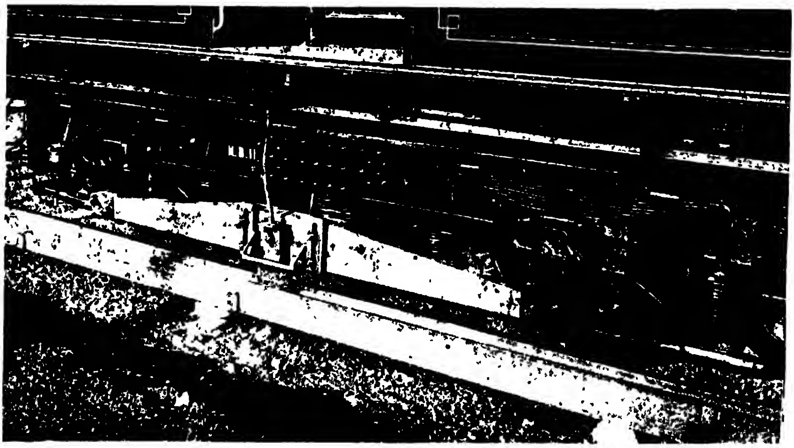


FIG. 238.—Collector Shoe for 1200-volt Side-contact Conductor Rail (Manchester-Bury Section, L.M.S. Railway). The shoe is shown in position against the conductor rail, and the efficient manner in which the latter is protected should be noted. (The protective covering over the upper part of the shoe is not in position.)

to some extent on inter-urban railways in America, its use on a large railway system could not be tolerated, both on account of the complication involved in the overhead conductors and the liability of the trolley wheel to leave the trolley wire. In practice, therefore, a bow or pantagraph collector, together with a level trolley wire, must be employed. The bow collector has the smaller inertia, but is not so readily adaptable to the collection of large currents as the pantagraph collector. Moreover, the bow collector must always be run trailing. Hence for reversible operation, either duplicate bows or a reversing bow must be employed. On the other hand, a pantagraph collector is reversible, but, on account of its greater inertia, requires a greater pressure to maintain contact with the trolley wire than a bow collector.

The collector, whether bow or pantagraph, is usually maintained in

* The current-collecting capacity of the larger wheels may be as high as 800 amperes at low speeds. With a level trolley wire, currents of 200 amperes have been collected at speeds of from 50 to 60 ml.p.h.

contact with the trolley wire by means of springs, while the raising and lowering operations are performed by air cylinders.

A typical **bow collector** is illustrated in Fig. 239. Collectors of this type were formerly in service on the single-phase, 6600-volt, suburban lines of the London, Brighton, and South Coast Railway (now a portion of the Southern Railway and converted to direct-current working). The

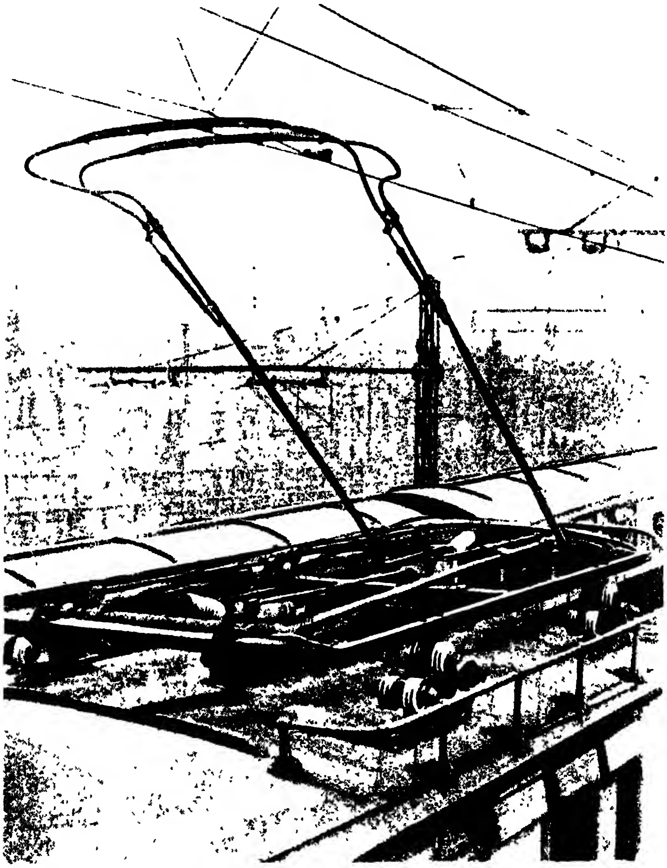


FIG. 239.—Bow Collector for Single-phase Motor-coach.

bows operate over a wide range of positions, the lowest position of the trolley wire being about 14 ft. above the rails, and the highest position 21 ft. Separate bows are provided for each direction of motion, and the bows, when lowered, lie inside each other. Each bow consists of a light tubular framework fixed to a shaft, which is carried on a channel-steel framework supported upon a double set of porcelain insulators. The top portion or contact strip is renewable. It is of aluminium and is grooved for the reception of a lubricant (a mixture of vaseline and graphite). Normally a contact strip had a service life of about 6000 miles.

The bow is maintained in the raised position by means of an air

cylinder acting against a set of springs, the piston-rod and springs being connected to levers on the shaft (the piston-rod being insulated from the shaft). The springs and levers are arranged to give a uniform pressure (of about 12 lb.) between the bow and the trolley wire over the whole operating range.

The air cylinders are supplied with compressed air* from a distributing valve, which is operated by the reverser, so that the bow in

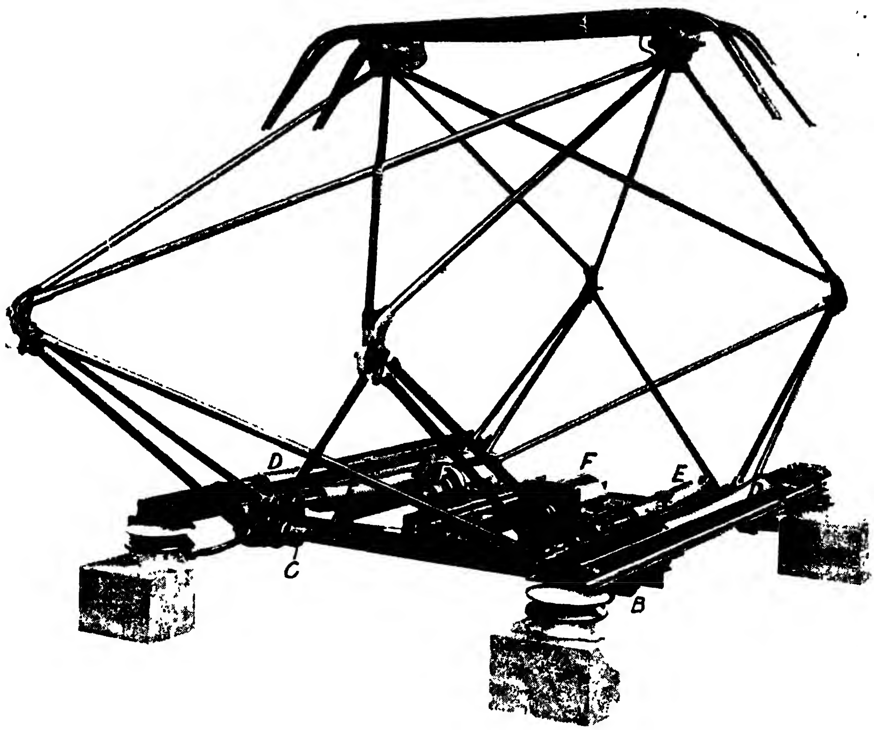


FIG. 240. Metropolitan-Vickers Pantagraph Collector.

contact with the trolley wire corresponds to the position of the reverser. Thus, when the train is reversed, the bows change over automatically as soon as the reverser is thrown to the "reverse" position. In changing over, the second bow is raised before the one in contact with the trolley wire is lowered.

When a single bow collector is required to operate in both directions of motion, the upper portion of the framework is fitted with a small **reversing bow,** which is spring controlled independently of the main framework; the latter being controlled by springs and air pressure in the usual manner. The auxiliary bow forms the current collector proper and accommodates itself to slight variations in the height of the trolley

* A hand pump is provided for raising the bow when there is no air supply.

wire, large variations in height being taken care of by the main framework. Bow collectors operating on this principle are shown in Fig. 347 (p. 484). In this case (which refers to a three-phase railway) the main framework of each collector is fitted with two auxiliary bows, which are insulated from the framework, since the wires with which they make contact belong to different phases of the supply system.

A **pantagraph collector for heavy-current locomotive service** is illustrated in Fig. 240. The view shows the collector in the normal operating position. Details of construction are as follow—

The contact portion consists of two pressed-steel pans *A*, of channel section, each of which is fitted with two renewable copper strips which

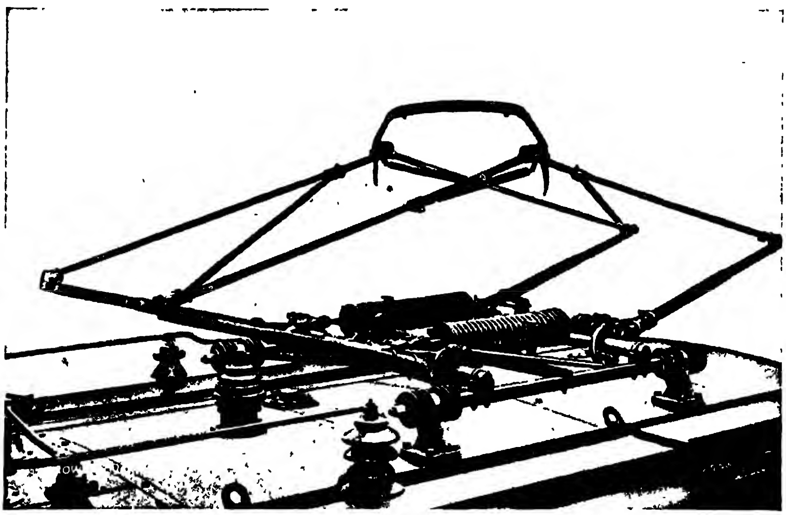


FIG. 241.—Brown-Boveri Pantagraph Collector for Single-phase Locomotives.

form the current collector proper. The pans are attached to light aluminium castings, which are pivoted to the top of a pentagonal framework, the castings being so designed that they will break in the event of the pans fouling any obstruction. The castings are spring-supported and allow the pans limited swivelling and vertical motions. The pans are, therefore, able to follow small irregularities in the level of the trolley-wire without any movement of the pantagraph.

The pantagraph framework is constructed of high-grade, light-gauge, steel tubing, with four sections, which are jointed at the corners. The lower sections are fitted to shafts, which are carried in ball bearings fixed to the main framework, the latter being fixed to the supporting insulators. Each shaft is fitted with two cranks, one (*B*) being located at the end of the shaft, and the other (*C*) between the bearings. The cranks *B* are connected to springs *D*, which are adjusted to balance most of the dead weight of the moving framework and pans. The other cranks (*C*) are connected by springs *E* to corresponding cranks fitted to countershafts, which are actuated by single-acting pneumatic cylinders *F*, such that when air is admitted to these cylinders the springs *E* are stressed

and the pantagraph is raised. Releasing the air from the cylinders therefore causes the pantagraph to be lowered. Equalizing links connecting the shafts ensure that the pans rise and fall vertically.

The cranks and springs are so designed that the variation of pressure on the trolley wire does not exceed 10 lb. over the whole working range of the collector. The average working pressure is 27 lb., but any value

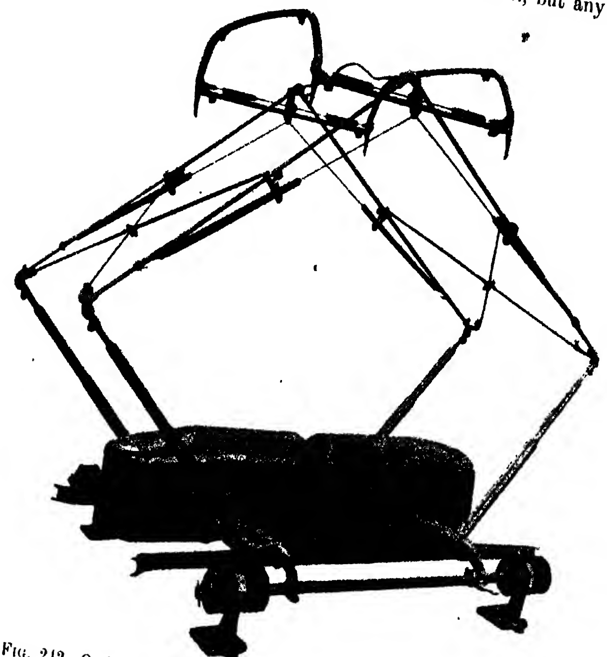


FIG. 242. Oerlikon Pantagraph Collector for Single-phase Locomotives.

between 15 and 35 lb. can be obtained by varying the stroke of the pistons by means of adjustable collars inside the cylinders.

The extremities of the pans are of the inverted-horn shape to prevent the pans fouling the trolley wires at crossings, and also to prevent a sagging trolley-wire becoming entangled with the pans.

A **pantagraph collector for moderate currents** (150 A.) and high-voltage (15,000 V.) is illustrated in Fig. 241. In this case the collector proper is of the bow form and is pivoted at the top of the pantagraph framework. The bow is fitted with supplementary springs and readily adapts itself to irregularities in the level of the trolley-wire. When the direction of motion is reversed the bow automatically reverses. The collecting strip is of aluminium and is lubricated in the same manner as that of the bow collector illustrated in Fig. 239.

Fig. 242 illustrates an alternative design of pantagraph for single-phase

locomotives. Two auxiliary bows are fitted, this arrangement being adopted in cases where a single collector is employed on a locomotive. The distance apart of the bows is sufficient to bridge the section-insulators in the trolley wire, thereby avoiding flashing at these points. A further feature is the central arrangement of the springs and operating cylinder, and the protection of these parts by a cover.

Collectors of these types are used to a considerable extent on European single-phase railways and are preferred to pan pantagraphs. They have given very satisfactory service on the largest single-phase (15,000 V.) locomotives in operation on these railways.

For direct-current railways, operating at 1500 and 3000 volts, the pan type of pantagraph collector is usually employed on account of its greater current-collecting capacity. Pans of the form illustrated in Fig. 240 can readily be designed for collecting the currents required by the largest direct-current locomotives. For example, currents of 2000 amperes have been collected at speeds of 40 ml.p.h. by a collector having two pans (with inserted copper bars), each pan being 5 in. wide by 42 in. long.

Power Supply for Brakes and Ventilating Apparatus

Power brakes* require either a supply of compressed air or means for creating and maintaining a vacuum. In the former case an electrically-driven compressor and air reservoirs are required, together with means for controlling the motor so as to maintain the air pressure within prescribed limits. In the latter case a vacuum pump, or exhauster, is required, together with means for controlling the speed of the motor to give the degree of vacuum desired.

Compressors. The compressor is usually of the single-stage two-cylinder, single-acting type, and is directly connected to the motor. With compressors for motor-coaches, a moderate speed motor is adopted in order to reduce the weight, and the compressor is driven through double-helical spur gearing.

The single-stage compressors for use on motor-coaches and locomotives are built in capacities up to 100 c. ft. (piston displacement) per minute at normal air pressure (80 to 90 lb. per sq. in.). Larger compressors are of the two-stage type, with three or four cylinders and an inter-cooler between the low- and high-pressure cylinders.

Fig. 243 shows the general construction of a geared single-stage compressor, a large number of which are in service on the locomotives of the Swiss Federal Railways. The air is drawn through a hair filter *A* into the crank case, from which it passes into the cylinders through inlet valves *B* located in the tops of the pistons. The delivery valves *C* are located in the cylinder heads, to which the delivery pipe *D* is connected. The lubrication is automatic; self-oiling rings being employed for the crank-shaft bearings, and a gravity system, with syphon feed, for the crank-pin bearings and pistons. For example, the (thick) cylinder oil is contained in a reservoir adjacent to the cylinder heads, and is heated by passing the compressed air from one of the cylinders through channels *E* in this reservoir. The oil then syphons through the wick *F* and the pipes *G* to

* A description of the mechanical equipment for compressed air and vacuum brakes is given at the end of Chapter XVI.

hollow chambers *H* in each end of the crank-shaft, from which it is distributed, by centrifugal force and the ducts *K*, to the crank-pin bearings. The surplus oil is thrown into the crank-case and mingles with the air entering the cylinders, thereby providing lubrication for the gudgeon pins, valves, and pistons. The gearing is located inside the crank-case, and the driving motor *M* is mounted on an extension of the bedplate.

The motor is of the series type whether the supply is direct or alternating. Single-phase motors for this service are now built with only exciting and commutating-pole windings after the manner of modern

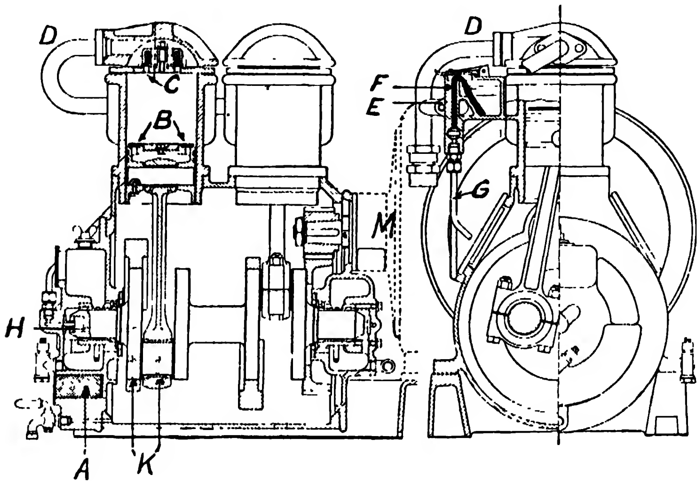


FIG. 243. Oerlikon single-stage Air Compressor for Locomotives.

traction motors. In all cases the motor is controlled by a single contactor which is actuated by air pressure. In some cases, however, the compressors are of the rotary type.

Automatic pressure regulator. A simple pressure regulator or governor for controlling a small compressor motor operating from a low-voltage (600 V.), direct-current circuit, is illustrated in Fig. 244. The operating mechanism consists of a piston *A*, which is pressed against a diaphragm *B* by a strong spring *C*, the other side *D* of the diaphragm being connected to the main reservoir. The piston operates the contactor *E* through a linkwork which is designed to give a quick closing and a quick opening action to the contacts. The governor is designed so that the contactor will open at a given air pressure and close when a slight reduction in pressure takes place, the difference between the opening and closing pressures being adjustable between 8 and 15 lb. per sq. in. The air pressure at which the contactor opens depends on the compressive force of the spring, and the latter can be adjusted, within certain limits,* by means of suitable screws in the closed end of the cylinder. The contactor is provided with a magnetic blow-out and connects the motor directly to the circuit, the motor being designed so that the initial current-rush

* The standard limits are: 40–60; 65–100; 100–140 lb. per sq. in.

on a 600-volt circuit does not exceed about twice the normal running current.

Fig. 245 shows an automatic pressure regulator which is adjustable over a large range of pressure and can be adapted to control the largest motor-driven compressors employed on locomotives. The contactor is actuated on the servo-pneumatic principle under the control of a spring-loaded diaphragm, and provision is made for non-automatic control when this is desired. A number of types of contactors are available according to the operating voltage and the nature of the current; typical

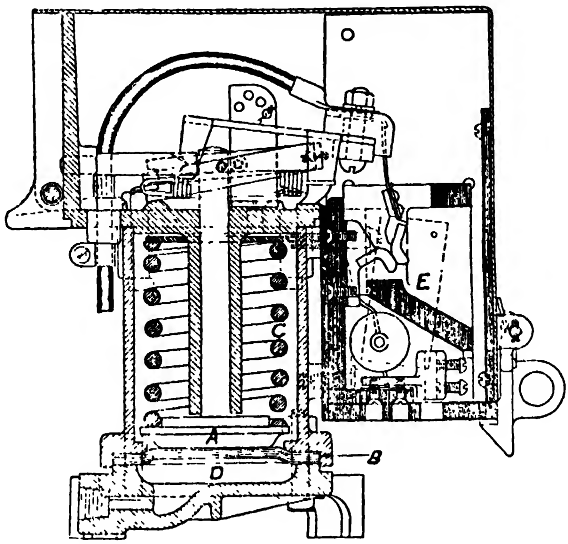


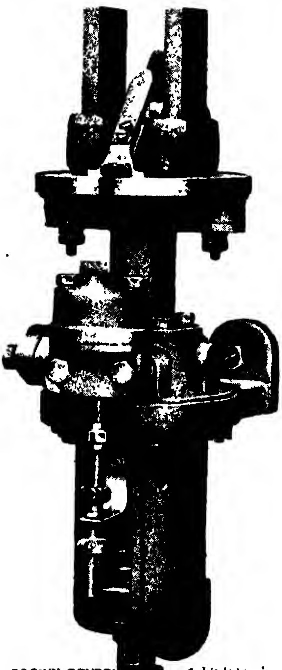
FIG. 244.—B.T.-H. (Type ML) Governor for Controlling Air-compressor Motor.

direct- and alternating-current types are shown in Fig. 245. In all cases the contacts operate with a quick make and break, the closing being effected by springs and the opening by air pressure.

The operation is as follows: The chamber *A*, above the diaphragm *B*, is supplied with air from the reservoir, which tends to depress the diaphragm against the action of the spring *C*, the initial compression of which is adjustable by the sleeve-nut *D*. A striking lever, *E*, is fixed to the upper spring-plate and may engage either of the adjustable tappets F_1, F_2, which are attached to the spindle of the exhaust valve *G*. If the compressor is running, and the pressure in the reservoir is rising, the striking lever will be moving downwards towards the lower tappet, and the valve *G* will be open to atmosphere, due to the upward force of the flat spring *H*. When the lower tappet is engaged this valve is closed and the spring-loaded inlet valve *J* is opened by the downward movement of *G* and *H*. Compressed air (from the reservoir) is then admitted to the chamber *K* above the valve *G*, and thence through ports to the underside of piston *L*, which is forced rapidly upwards, thereby opening the contactor *M*, and stopping the compressor. The air supply is maintained to

the chamber K and under the piston M until the upper tappet is engaged (due to the pressure in the reservoir having fallen) by the upward movement of the striking lever E. Valve G is then opened, and valve J automatically closes. The chamber K is thereby connected to atmosphere and the release of the air pressure from the piston L causes the contactor to close automatically by the action of springs.

Non-automatic operation of the pressure regulator is obtained by means of a special three-way cock in conjunction with an external



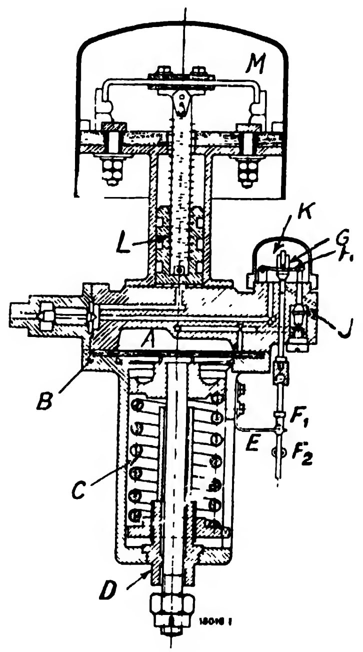


Fig. 245. Brown-Boveri Automatic Pressure Regulator.

Note.—The regulator shown in left-hand illustration is for controlling a 1,500-V. direct-current motor, that shown in the right-hand illustration is for a 220-V. single-phase motor.

connection to the chamber K. When the contactor has been opened in the ordinary way by the pilot valves the cock is moved to a second position, which shuts off chamber A from the reservoir and opens the underside of piston L to atmosphere, thereby causing the contactor to close again and the compressor to re-start. The compressor is stopped by moving the cock to a third position which admits compressed air to the underside of piston L.

Exhauster. The exhauster or vacuum pump (which is used with vacuum brakes) is usually driven by a slow speed motor through a spring coupling. In some cases the motor is run continuously at slow speed (for the purpose of maintaining the vacuum), and is automatically switched over to full

speed when the brake valve is moved to the " off " or " release " position. In other cases the motor is controlled by an automatic governor, which is arranged to start the motor when the vacuum falls to 15 in.

Ventilating plant. Blowers are required on locomotives when forced-ventilated motors are used. In some cases a single blower is employed which delivers air at a small pressure (6 to 8 in. of water) into a central duct—built into the underframe of the locomotive body—from which it is distributed to the motors. In other cases, with large frame-mounted motors, a separate blower is provided for each motor. The blowers are then mounted on the motor frames, and two or more blowers are coupled together and driven by a single motor. The motor is of the series type and is controlled by a single contactor when the supply is direct. With low-voltage, single-phase blower motors, each driving two or more blowers, two-step starting is employed. The control switch is in this case connected in the main circuit of the motor, and the starting resistance is cut out automatically when approximately half speed is reached by a " counter E.M.F." contactor (the operating coil of which is shunt wound and is connected across the brushes of the blower motor).

Power Supply for Auxiliary Circuits

The auxiliary circuits requiring a supply of current are: (1) control; (2) motors for driving the compressors, exhausters, and blowers; (3) lighting; (4) heating.

With **single-phase equipments** these circuits are supplied from tappings on the main transformer, a voltage of about 220 volts being employed for the auxiliary motors, and also for the control and lighting circuits, except in cases where a low-voltage, direct-current, train-lighting system is already in existence. The train-heating circuits are usually supplied at a voltage between 600 and 1000 volts, in order to limit to moderate values the current to be carried by the heating bus-line cable and couplers, as in some cases from 300 to 400 kW. may be required for heating purposes. Usually three tappings are provided in order that the degree of heat may be varied when desired, the control switch being located in the driver's cab.

With **high-voltage, direct-current equipments** the compressor, exhauster, and blower motors are usually supplied directly from the traction circuit when the voltage does not exceed 1500 volts, but for higher voltages these machines are supplied at low voltage (100 to 125 volts) from a motor-generator set, which also supplies the control and lighting circuits. In some 1500-volt installations in America, however, the control and lighting circuits are supplied at 600 volts. In these cases, on account of the low ratio of the primary and secondary voltages, a " dynamotor " or " reducer " is more efficient and less costly than a motor-generator set for supplying the 600-volt circuits.

'Dynamotor or reducer. In this machine the generator armature is connected in series with the motor armature, and therefore a portion of the current (viz. the armature current of the motor) required by the control and lighting circuits is obtained directly from the supply system. The arrangement is, in fact, similar to that of an auto-transformer. The reducer is usually built with a common field frame and armature core

which is wound with two windings. The ratio of turns in these windings is approximately equal to the ratio $(V - 600): 600 = (V/600 - 1): 1$, where V is the line voltage and 600 is the voltage required by the control and lighting circuits. For this service the machine is usually provided with two series windings and a shunt winding—connected as shown in Fig. 246—the connection to the lighting and control circuits being taken from the junction of the two series windings. When there is no load on the low-voltage circuit, both armatures operate, in series, as motors and all the field windings act cumulatively, the excitation being derived almost entirely from the shunt winding. When the low-voltage circuit is loaded, the armature connected to the line acts as a motor, and the other armature

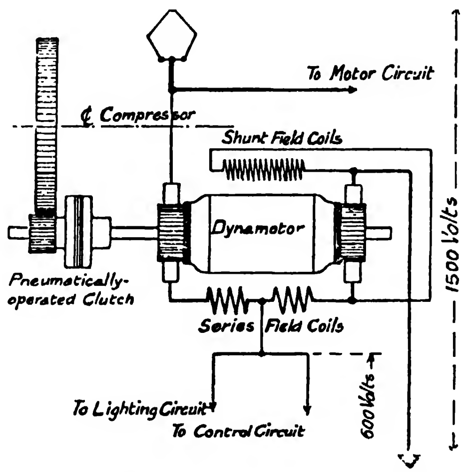


FIG. 246.—Diagram of Circuits of Dynamotor.

acts as a generator. Moreover, the series field winding connected in the generator circuit now acts differentially with respect to that of the motor and the shunt winding. By suitably proportioning the two series windings, the flux and speed can be maintained practically constant at all loads.

In America the dynamotor has been combined with the compressor and the blower, the latter being mounted on an extension of the armature shaft, while the former is driven through a pneumatically-operated clutch controlled by the air pressure in the main reservoir. In this manner a considerable saving in weight and space is obtained. Of course, with a machine of this type the speed will not remain constant at all loads, but will be lower when the compressor is working, due to the additional series field ampere-turns produced by the motor.

Rotary transformer. When the lighting and control circuits are to be supplied at 100-125 volts, and the auxiliary motors operate direct from the 1500-volt traction circuit, the low-voltage power demand is relatively small and may not exceed 2 kW. with motor-coach trains. In these cases (especially when the voltage of the traction circuit is not subject to large variations) a rotary transformer is to be preferred to a motor-generator

set on account of its light weight, cheapness, and higher efficiency. This machine is similar in construction to a reducer (i.e. it has a single frame and armature core), but the high-voltage and low-voltage circuits are not interconnected. The motor portion of the machine must, therefore, be designed for the full line voltage, and also to withstand being switched directly on to the supply at starting. The field windings are arranged similar to those of the reducer in order to obtain approximately constant flux and speed at all loads.

Motor generator. When the whole of the auxiliary circuits, except the heating, are to be supplied at low voltage, the power demand may reach 30 or 40 kW. in the case of a large locomotive with forced-ventilated

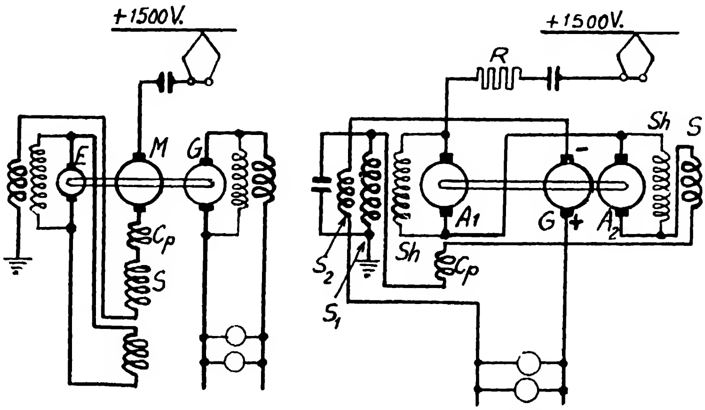


FIG. 247. FIG. 248.
Connections of Self-regulating Motor-generator Sets. (Brown-Boveri and B.T.-H.)
(Cp, commutating-pole winding; Sh, shunt winding; S, S_1, S_2, series windings.)

motors. In these cases motor generator sets must be employed. To simplify the starting apparatus the motor must start as a series machine. Unless a permanent load (e.g. a blower) is connected to it, the motor must have additional excitation to prevent large changes of speed with variation of the generator output. This additional excitation may be supplied either by the generator or by an exciter.

Self-regulating motor generators. On main-line long-distance service the voltage of the lighting circuit must be maintained constant irrespective of voltage fluctuations in the traction circuit. This could be effected by providing a special lighting motor-generator set (of small output) and controlling the voltage by an automatic regulator. But a more satisfactory solution is to incorporate features into the main motor-generator set so that the generator voltage is maintained constant even with large variations of the supply voltage. Two schemes which have been developed for this purpose will now be considered, the connections being shown in Figs. 247, 248.*

In the **Brown-Boveri** method an exciter is employed the magnetic circuit of which is worked at low magnetic saturation. The connections

* Both of these schemes are patented.

are shown in Fig. 247. The generator, G, is an ordinary compound-wound machine, giving constant voltage when driven at constant speed. The motor, M, has two field windings, viz., a main series winding and an auxiliary separately-excited winding which is connected across the armature of the exciter. The function of the separately-excited winding is to maintain the speed of the set approximately constant irrespective of variations of the supply voltage. The exciter has also two field windings, viz., a self-excited shunt winding and a separately-excited (series) winding connected in the motor circuit.

The resistance of the shunt winding of the exciter is so adjusted that, in conjunction with the unsaturated magnetic circuit, any variation of

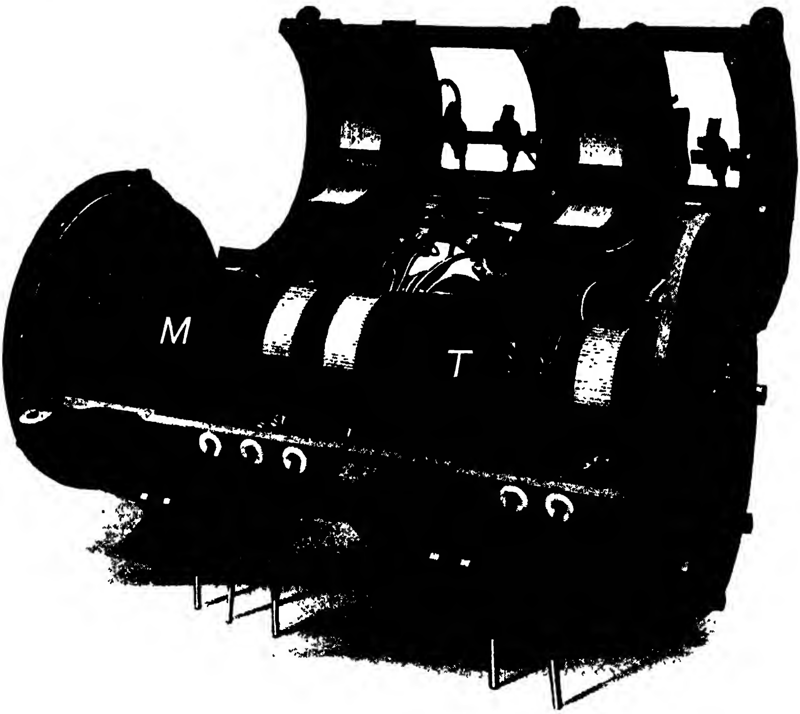


FIG. 249. B.T.-H. Self-regulating Motor-generator Set, Upper Half of Frame Opened.

speed from the normal value causes a large variation of the armature voltage, a rise of speed causing a rise of voltage, and vice versa. This voltage variation produces corresponding variations in the current supplied to the separately-excited winding of the motor, and by suitably proportioning the ampere-turns supplied by the two windings the speed can be maintained practically constant over a wide range of load and line voltage. For example, with a particular set and a line-voltage variation of 50 per cent, the variation of speed at full load was about $\pm$ 3·5 per cent, and the variation of generator voltage $\pm$ 4·6 per cent. At no load the variations were slightly smaller.

The connections of the **B.T.-H. self-regulating motor generator** are

shown in Fig. 248, and a typical set is illustrated in Fig. 249. The set consists of a differentially-compounded motor, M, coupled, both mechanically and electrically, to a cumulatively-compounded rotary transformer T, the two motor elements of the set being connected in series with each other. For 1500-volt circuits, the motor M is a single-commutator machine, but for higher voltages this machine would be built with two armature windings and commutators, which would be connected permanently in series.

In Fig. 248 the armature of the motor (M, Fig. 249) is denoted by A_1, and the three excitation windings of this machine by Sh, S_1, S_2. Of these, the series winding S_1 is employed for starting, and is short-circuited automatically by a contactor when the set attains normal speed. The motor then runs as a differentially compounded machine, the differential series field winding S_2 carrying the generator current.

The rotary transformer (T, Fig. 249) is cumulatively compounded; the shunt field winding being connected across the motor armature A_2, and the series winding being connected in the motor circuit.

A permanent resistance R is connected in the "line" circuit to prevent violent fluctuations of the line voltage, causing flashovers at the commutators of the motor elements.

With this arrangement of machines and connections the percentage variation of voltage at the terminals of the generator can be made considerably less than the variation of line voltage. For example, with a particular set, a variation of line voltage from 1,500 to 1,000 volts caused, at full load, a corresponding variation of generator voltage from 132 to 118 volts. The corresponding variation of speed was from 1,460 r.p.m. to 1,275 r.p.m.

CHAPTER XV

ROLLING STOCK FOR TRAMWAYS AND RAILLESS ROUTES

I. Tramways Rolling Stock

The double-deck car, mounted on either a single truck or bogie trucks, is used almost exclusively on tramways in this country. The upper deck is usually covered and the sides are provided with drop sashes.

The single-deck car has a limited application in this country and is adopted where the conditions are unfavourable for double-deck cars. In America and on the Continent, however, the climatic conditions necessitate a closed car, and the double-deck car is the exception. Moreover, in some American cities there is insufficient head room for the ordinary double-deck car, and the recent introduction of this type of car in New York required a special design, having a total height of 12 ft. 10 in. (against 16 ft. for a standard British design). The type of car is, of course, largely influenced by the traffic conditions, which in America require a car which can be loaded and unloaded in the minimum time.

Choice of car. The more important considerations which affect the choice of a car for a tramway system are: (1) gauge, curvature, and contour of the track; (2) height of the lowest bridge from the track; (3) class of traffic.

The **gauge** influences the total width of the car body, and, consequently, the passenger accommodation. With the usual arrangement of longitudinal side-seats on the lower deck, the width of the car will affect the gangway, but not the seating accommodation. On the upper deck, however, where the seats are arranged transversely, the seating capacity will be considerably restricted on narrow-gauge lines. Thus, with standard (4 ft. 8½ in.) gauge, four passengers can be comfortably accommodated in each row, but with 3 ft. gauge it is only possible to accommodate two passengers in each row (unless the gangway is made very narrow). The width of the car is governed, to some extent, by the width of the street, as it is necessary to provide a minimum clearance of 15 in. between passing cars, and between cars and any standing work. With standard gauge the maximum width of car allowed is about 7 ft.

The **curvature of the track** affects the wheel base, which, with single-truck cars, affects the length of the car. A curve of 30 ft. radius can be negotiated by a single-truck car with a rigid wheel base of 6 ft., but to avoid excessive track wear the wheel base should not exceed 5 ft. 6 in. Thus, when this type of truck is adopted, the length of the car is restricted. If the nature of the traffic warrants a larger car, either double (or bogie) trucks or a radial truck must be employed.

The **contour of the line** affects not only the car but also the electrical and braking equipment. Light single-truck cars are alone permissible on heavy gradients.

The **height of the lowest over-bridge** on the system affects the head

room on each deck, and exceptionally low bridges may necessitate the use of single-deck cars.

The **class of traffic** is usually the feature which decides the length of the car. Heavy traffic requires large cars mounted on bogie trucks, but if heavy gradients have to be negotiated, smaller, single-truck cars may be necessary.

TRAMCARS

Typical British cars. A modern double-deck car mounted on a single truck (of the Peckham swing-axle type) is shown in Fig. 250, and the principal dimensions, weight, etc., are given in Table IX. The car is

TABLE IX

DATA OF TRAMCARS AND TROLLEY-BUSES

Reference*	Tramcars (Double End).				Buses.	
	CDDS	*CDDB*	*SDB*	*LWSDS*	*SDCE*	*CDD*
Length over all	30′ 0″	33′ 10″	33′ 9″	33′ 4½″	26′ 0″	26′ 0″
Length of body (over corner posts)	16′ 4″	22′ 2″	24′ 10″	22′ 8″	25′ 0″	21′ 0″
Length of each platform	6′ 0″	5′ 10″	3′ 8½	4′ 10″	4′ 0″†	4 3″§
Width over all (maximum)	7 0½″	7′ 1″	6′ 10″	8′ 4″	7′ 4″	7′ 4″
Clear height of lower saloon at centre	6′ 4″	6 2¾″	8′ 1¾″†		6′ 3″	6′ 2″
Clear height of upper saloon at centre	5′ 10½″	6′ 1¾″				6′ 2″
Height of floor above rail	2′ 10″	2′ 9½″	2′ 9½″	2′ 4″	2′ 10″	2′ 10″
Total height to top of trolley-board (from rails)	15′ 8″	15 8½″′		10′ 8	9′ 8″	15′ 2″
Total height over dwarf trolley standard (from rails)	16′ 1″	16′ 1½″		..	10′ 9″	16′ 3″
Number of seated passengers (lower deck)	22	32	36		36	27
Number of seated passengers (upper deck)	36	46	.	..		28
Class of truck	Peckham	maximum traction	maximum traction	composite radial	two axle chassis	three axle chassis
Wheel-base	7′ 6″	4′ 6″	4′ 6″	12′ 0	15′ 6	15′ 6″
Diameter of wheels	32½″	{31¾″ 21¾″}	31¾″ 21¾″	28″	40″	40″
Centres of bolsters	.	10′ 6″	10′ 6″	..		
Motor equipment	2-40 h.p.	2–60 h.p.	2–50 h.p.	2-50 h.p.	1-50 h.p.	1–60 h.p.
Weight of car equipped	10¼ tons	14¾ tons	14½ tons	10¼ tons	7 tons	8 tons
Weight of car with passengers	14½ tons	19¾ tons	16¾ tons	12½ tons	9½ tons	11½ tons

* *CDDS*, British Standard covered double-deck, single-truck car; *CDDB*, L.C.C. covered double-deck bogie car; *SDB*, L.C.C. single-deck bogie car; *LWSDS*, Brill standard light-weight single-deck, single-truck car with high-speed frame-mounted motors, double reduction gearing and cardan-shaft drive; *SDCE*, single-deck, centre entrance trolley-bus; *CDD*, covered double-deck trolley-bus (rear entrance).
† Clerestory roof. ‡ Centre entrance. § Platform at rear only.

provided with a covered top deck and vestibuled platforms on the lower deck.

The standard double-deck bogie car of the London County Council Tramways is shown in Fig. 251, data of which are given in Table IX. This car is provided with both trolley and plough collectors (the latter being removable) for operation on the overhead trolley and conduit sections of the tramway system.

Construction. The **car body** is built principally of wood.

The **underframe** of a single-truck car is constructed either of oak (with the principal members reinforced by steel sections or steel plates), or entirely of rolled steel sections; but that of a bogie car is constructed

Fig. 250.—Modern British Double-deck Car with Covered Upper Deck and Vestibule (Built by the Brush Electrical Engineering Co.).

FIG. 251.—Standard London County Council Tramcar arranged for Operation on Conduit and Overhead Trolley Sections of the Tramways.

entirely of steel sections, as, in this case, the entire weight of the car must be supported at two points, viz. the truck bolsters.

The **floor** is of pine boards, with slats of hard wood for wearing purposes. Two or more removable traps are fitted over the motors to allow the latter to be inspected.

The **roof** of cars which are equipped with trolleys must be specially reinforced to withstand the strains produced by the trolley. It is the usual practice to fix the trolley to a "trolley board," extending nearly the whole length of the roof, and to construct the latter with alternate car-lines of steel.

In order to comply with statutory regulations, cars operating on British tramways must be provided with life guards, head and rear

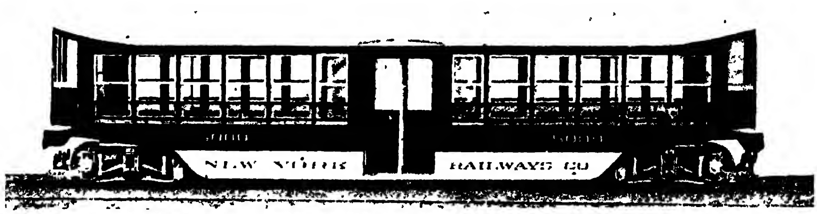


FIG. 252.—Centre-entrance, Single-deck, "Stepless" Car, built by the J. G. Brill Co. for the New York Conduit Tramways.

lights, destination indicators, gongs, mechanical brakes, and sanding gear.

Centre-entrance, "stepless" car. In large American cities the traffic conditions require a car which can be loaded and unloaded in a minimum time, and in which a large number of standing passengers can be accommodated. Moreover, it is customary to collect the fares of the passengers either upon entering or leaving the car. These features have resulted in the development of a centre-entrance car having an exceptionally low floor at the entrance.

A typical car is shown in Fig. 252. The car body and underframe are of steel, and the floor, window-posts, head-lining, and roof boards are of wood. The floor at the entrance is only 10 in. above the track rails, and at the motorman's compartments it is raised to 2 ft. 8¾ in. so as to clear the motors. At the ends of the passenger compartment, however, the floor is 16 in. above the rails. The low floor has necessitated the use of trucks with exceptionally low bolsters, the top of the bolster being only 12½ in. above the rails.

A number of double-deck cars have also been constructed with the centre-entrance, stepless feature. These cars are also in service in New York, and have had to be designed with the very low overall height of 12 ft. 10 in., in order to clear the viaducts of the elevated railways. These cars accommodate an exceptionally large number of standing passengers—42 on the lower deck and 41 on the upper deck—although the seating capacity (88) is only slightly greater than that (78) of the large double-deck cars on the London County Council tramways.

Modern tendencies in car design. The cars illustrated in Figs. 250, 251, when equipped with axle-mounted motors, are considered by some tramway engineers to be unable to meet successfully the demands of modern traffic in large cities, particularly when competing motor omnibuses operate over the same routes as the tramcars. A number of designs have accordingly been evolved with the object of (1) increasing the speed of loading and unloading, (2) reducing the weight of the car without reducing the strength and seating accommodation.

The first item, in so far as British cars are concerned, involves low-floor, or stepless, platforms and means for quickly distributing the passengers to the lower and upper saloons.

The weight of the car body may be reduced by the use of aluminium for the plating, panelling, mouldings, and interior fittings. A saving in the weight of the motors and trucks is possible by adopting high-speed motors (i.e. machines in which the armature speeds are approximately double those in general use), but in this case either double-reduction spur gearing or worm gearing must be employed. Both forms of gearing are now available for tramcar equipments.

Recently a cardan shaft drive has been proposed, in which the (two) motors are wholly spring supported (by being mounted on a sub-frame fitted to the centre of the underframe of the car), and the power is transmitted through flexible couplings and cardan shafts to worm gearing on the driving axles.*

TRUCKS

Trucks for tramcars may be divided into two classes, viz. (1) single trucks, (2) bogie trucks.

Single trucks may be subdivided into three types, viz. (*a*) trucks in which the axles are maintained rigidly parallel (called rigid-axle trucks); (*b*) trucks in which the axles are allowed transverse oscillatory movement (called swing-axle trucks); (*c*) trucks in which the axles are allowed radial as well as transverse movement (called radial-axle trucks).

Bogie trucks may be subdivided into two types, viz. (*d*) the maximum traction or single-motor truck, in which the pivotal centre is displaced from the centre of the truck towards the driving axle; (*e*) the equal-wheel truck, in which the pivotal centre coincides with the centre of the truck. Each of these types may be fitted with either rigid or swing axles.

The **choice of the truck** is influenced by the length of the car and the curvature of the track. Thus a car 18 ft. over the body can be accommodated on a single truck with rigid or swing axles, provided that the curvature of the track will allow of the use of an 8-ft. wheel-base. With the usual wheel-base of 6 ft., the length of the car is limited to 16 ft. over the body and 27 ft. over the platforms. Longer cars, up to 23 ft. over the body and 33 ft. overall, can be accommodated on single trucks with radial axles, but for cars of greater length bogie trucks must be employed, the wheel-base of which, for tramway purposes, is usually from 4 ft. to 4 ft. 6 in.

Rigid-axle single truck. The essential parts are: (1) the truck frame, which contains the guides for the axle-boxes; (2) the wheels, axles, and

* See *Tramway and Railway World*, LXIII, 235, 240.

the axle-boxes ; (3) the supports for the car body ; (4) the spring system ; and (5) the motor suspension. The relative positions of these parts are shown in Figs. 253, 254, which illustrate a truck in very extensive use.*

The **truck frame** consists of two forged-steel side frames *A*, held together by the end frames *B*, and the diagonal brace *C*. In each side frame two yokes are formed, which are machined to receive the axle-boxes *D*. The latter are provided with double "wings" or pockets for the reception of the springs *E*, which support the side frames and everything connected thereto.

The spring posts *F*, of which there are four to each side frame, are connected together at the top by the "top plates" *G*—to which the side-sills (or sole-bars) of the car body are fixed and at the bottom by the truss rods *H*. The posts pass through holes in the side frames, thereby maintaining car body and truck in their correct positions, and taking all the thrusts between these members.

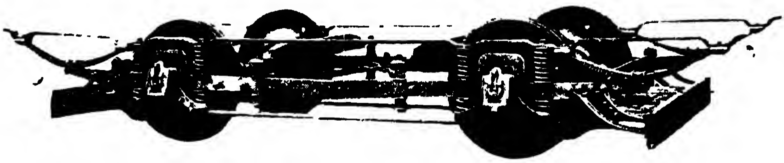


FIG. 253. Brill "21 E" Rigid-axle, Single Truck.

The car body is supported on the side frames by a compound spring system, consisting of eight spiral springs *J* and four semi-elliptic springs *K*, the function of the latter being both to damp the oscillations of the car body when the car is running at moderate speeds and to resist any side motion of the car body.

The motor suspension bars *L* are supported on the side frames by a double set of springs, and in this manner the unspring-borne load on the axle is about 50 per cent of the weight of the motor.

The **axle boxes** are of malleable iron (or, in some cases, of cast steel) and contain a bearing liner, which rests on the upper part of the axle journal. The lower portion of the box forms an oil well, and the journal is lubricated on the pad system. End play of the axle is limited by a check-plate which bears in a groove formed in the end of the axle. A sectional view of a typical axle box is shown in Fig. 255.

The **brake system** provides for a separate brake block to each wheel, the brake blocks being suspended from a pair of links carried from brackets fixed to the end frames of the truck (see Fig. 254). A recent development is the provision of *spherical seats*, where the links are hinged to the brackets and brake shoes, thereby forming an automatic adjustment for wear. The brake shoes for each pair of wheels are fixed to transverse bars *M* (Fig. 254), called "brake-beams," each of which carries a fulcrum for the brake levers *N*, to which the pull-rods from the operating spindles on the platforms are attached.

The pressure between the brake shoes is equalized by means of the

* Originally developed by the J. G. Brill Co., and known as the "21 E" truck. It is also manufactured by several firms in this country.

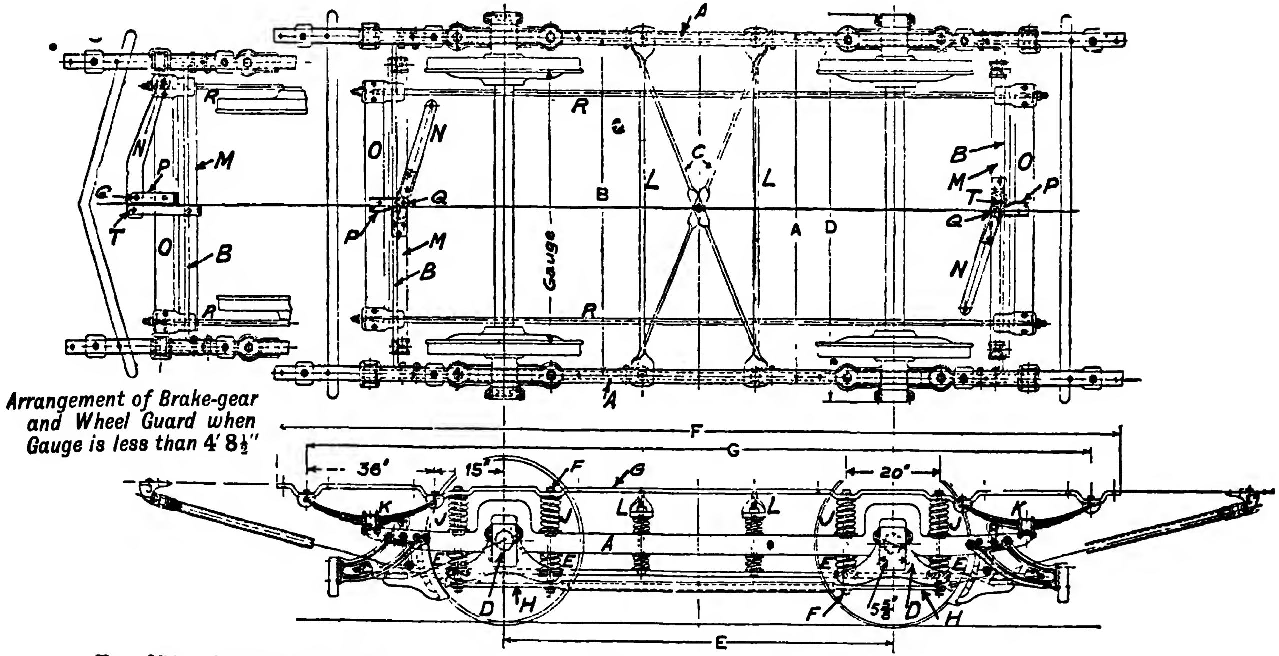


FIG. 254.—Outline Drawings of "21 E" Truck. NOTE.—The extended truss-rods are only used with long cars. (The dimensions, **A—G**, of a typical truck are given on p. 358.)

transverse bars O (called "equalizing levers"), which are connected together by the adjustable rods R. At the centre of each equalizing lever is fixed a bracket P, which is connected to the brake lever by a pin Q. The brake shoes are released by the combined action of gravity and springs, the latter being attached to the brake beams and to some fixed part of the truck, e.g. the wheel guards when spiral springs are used, and the end frames when flat springs are used.*

When an application of the brakes is made from, say, the forward end of the car, the front brake lever N turns about the fulcrum T, thereby moving apart the front brake beam and equalizing lever. If the rods R are properly adjusted, the front and the rear brake shoes

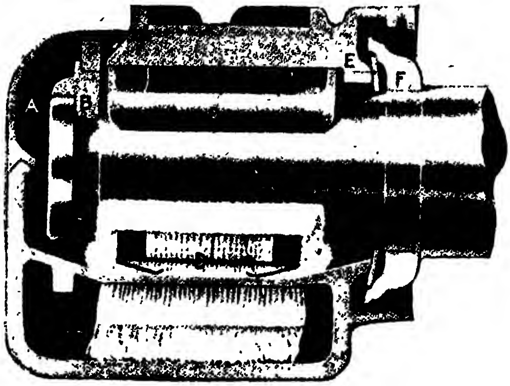


FIG. 255.– Brill Axle-box (Tramway Type). A, cover; B, check-plate; C, bearing; D, oiler; E, fibre washer; F, collar.

will be moved towards the wheels, the rear brake beam being moved forward by means of the rear equalizing lever. As soon as the front pair of brake shoes touch the wheels, the front brake beam becomes fixed, and the thrust is transmitted to the rear brake beam through the rods R and the equalizing levers. Thus the whole of the brakes are operated from one pull rod. The brake levers are duplicated in order that the brakes may be applied from either end of the car.

The following particulars refer to this truck—

	ft.	in.
Gauge	4	8½
Wheel base (**E**, Fig. 254)	6	0
Spring base of car-body springs (**G**)	14	6
Length over top plates (**F**)	15	7
Width over top plates (**A**)	6	0
Centres of top plates and side frames (**B**)	5	9½
Width overall (**D**)	7	0
Diameter of wheels		30
Diameter of axles		4
Diameter of journals		3½
Height from track rail to top plates with empty car body in position	2	1⅛
Weight without wheels and axles	3,000 lb.	

* See Fig. 258 for a detail view of the brake gear. Although this illustration refers to a radial-axle truck, the general arrangement of the brake beams, equalizing levers, brake levers, and pull-off springs is identical with that on a rigid-axle truck.

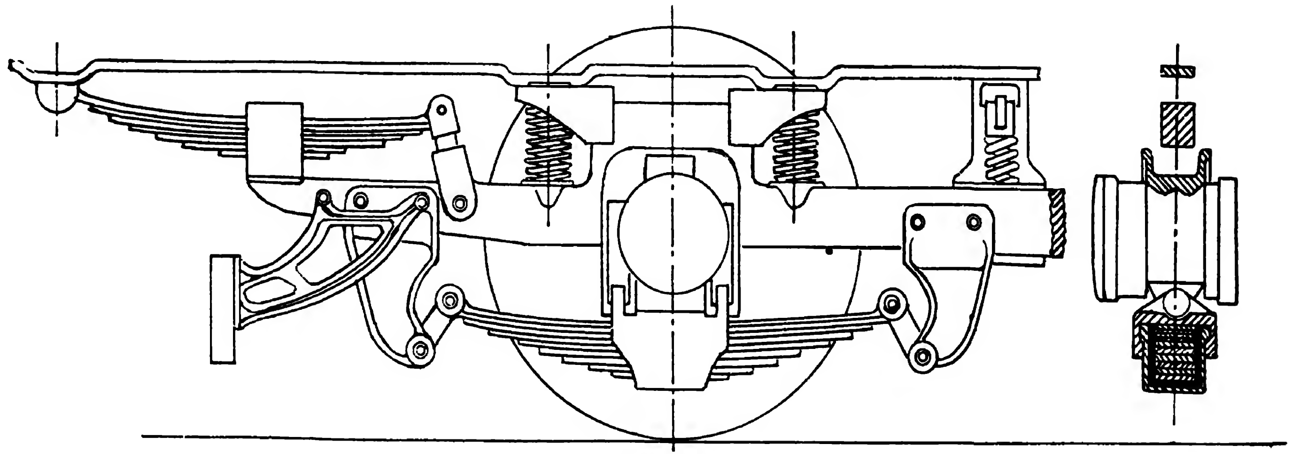


FIG. 256.—Detail of Peckham Swing-axle Truck.

Swing-axle single truck. This type of truck has been developed by the Peckham Truck Co. and the J. G. Brill Co. The side frames and spring system are similar to those of the 21 E truck described above, except that, with the latest type (P 35) of Peckham truck, the semi-elliptic springs in the 21 E truck are replaced by cantilever springs in order further to reduce the tendency of the car to "gallop."

The swing-axle device, or pendulum gear, is shown in Figs. 256, 257. In one case (Fig. 256) the axle-box springs are of the laminated semi-

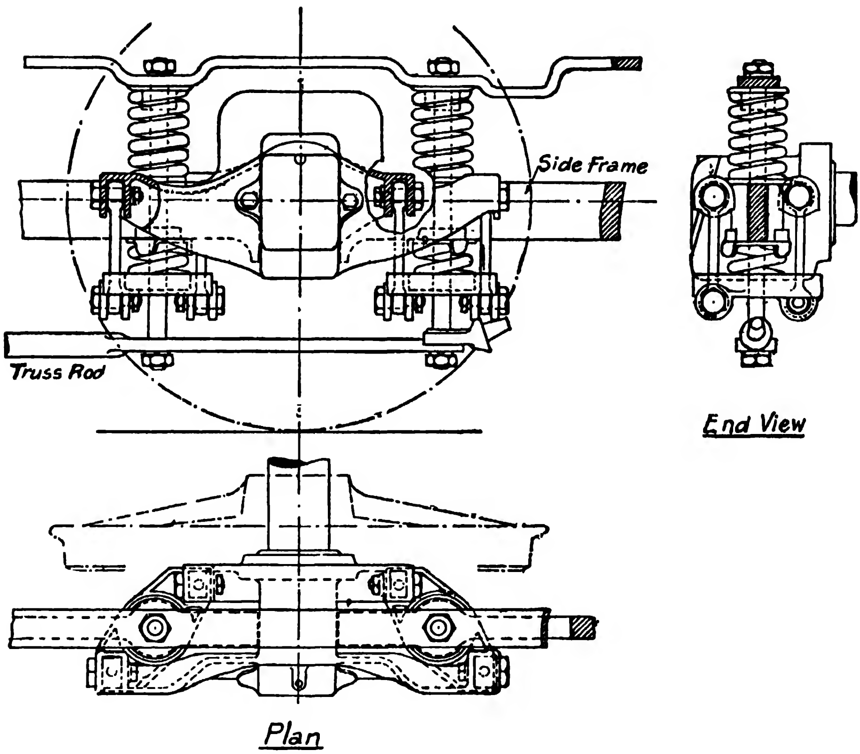


FIG. 257. Detail of Swing-axle Device for Brill "21 E. S.I.." Truck.

elliptic type, and their stirrups are hinged to saddles which are pivoted to the tops of the axle boxes. In the other case (Fig. 257) the axle boxes are provided with side extensions, from which the axle-box springs are carried by swing links. Thus, in both cases, the axles can move laterally *independently of the truck frame and car body*, and can therefore adapt themselves to irregularities in the track without transmitting the effects to the car body.

Trucks of this type are characterized by easier riding and freedom from side oscillations. Moreover, the blows delivered to the rail head by the flanges of the wheels are considerably smaller than with trucks of the rigid-axle type, so that the wear of the track and wheel flanges will

be reduced. Moreover, the lateral flexibility of the axles will tend to prevent "corrugation"* of the track rails.

In order that the transverse movement of the axle shall not be restricted by the motor suspension bars, these are fitted with swinging links, as shown in Fig. 258.

Radial-axle trucks. The term "radial-axle truck" is applied to a truck with two axles, which have a limited angular motion in a horizontal plane, independent of the truck frame, thereby enabling a truck with a long wheel base to operate on curves of short radius.

Two general principles have been adopted in the designs for radial-axle trucks—one in which the axle boxes are given freedom for movement in the side frames, by being suspended from certain points in the main truck frame; and the other in which two sub-trucks, each equipped with an axle and axle boxes, are pivoted to the main truck frame. Trucks built on the former principle are less complicated than those of the sub-truck type, but do not possess such good radiating properties on sharp curves. Radial-axle trucks without sub-trucks have been developed by the J. G. Brill Co. and the Peckham Truck Co. The latter firm has successfully developed a radial-axle truck of the sub-truck type. Typical trucks are illustrated in Figs. 258–260.

In all these trucks the side frames are provided with wide yokes (or pedestal jaws), so that the axle boxes can move longitudinally as well as laterally. The car body is attached to the top plates in the same manner as with the trucks previously described, but the thrust is taken by special blocks bearing against the upper part of the yokes.

In the **Peckham truck** shown in Fig. 258 (which is constructed without sub-trucks) the axle boxes are provided with side lugs, from which the supporting frames (which carry the main truck frame) are suspended by links with hemispherical ends. The motor suspension bars are hinged to the truck frame. Hence the wheels and axles can adjust themselves to the curvature of the track, and the axle can take up a position approximately radial to the curve. In this position of the axle the links become inclined and a couple is brought into operation, tending to restore the links to their normal (vertical) position when the car leaves the curve. The brake gear is a modification of the standard brake gear for single trucks, with features to allow for the angular movement of the wheels

The **Brill truck** (Fig. 259) is also constructed without sub-trucks, and is of the swing-link type, with two fixed pivotal points (one for each axle) on the centre line of the truck; the pivotal points being attached to the motor suspension bars.

The side frames are supported on swinging links, which are hung from springs located in "wings" on the axle boxes. These links have the upper end in the form of a hemispherical head, and have two pins fixed in the lower end, the pins engaging in grooves formed in the lower part of the frame yokes. Under normal conditions the links are vertical, and each pin has a full bearing in its groove. When the axle is deflected, the

* Transverse corrugations of small depth are formed in the head of the track rails by the transverse movement of the wheels across the rail head. Other conditions, such as weight carried on the axles, diameter of wheels, etc., also influence the formation of corrugations.

links take up an inclined position, in which one pin in each link leaves its groove. In this position of the links the weight of the car, acting on the pins, exerts a couple tending to restore the links to the normal position. By means of the motor frames and the suspension bars the axles are pivoted to two king pins, which are fixed to the cross frames and are located on the centre line of the truck.

When the car is rounding a curve, the centrifugal force acting on the car body is transmitted to the king pins, and the truck frame—being

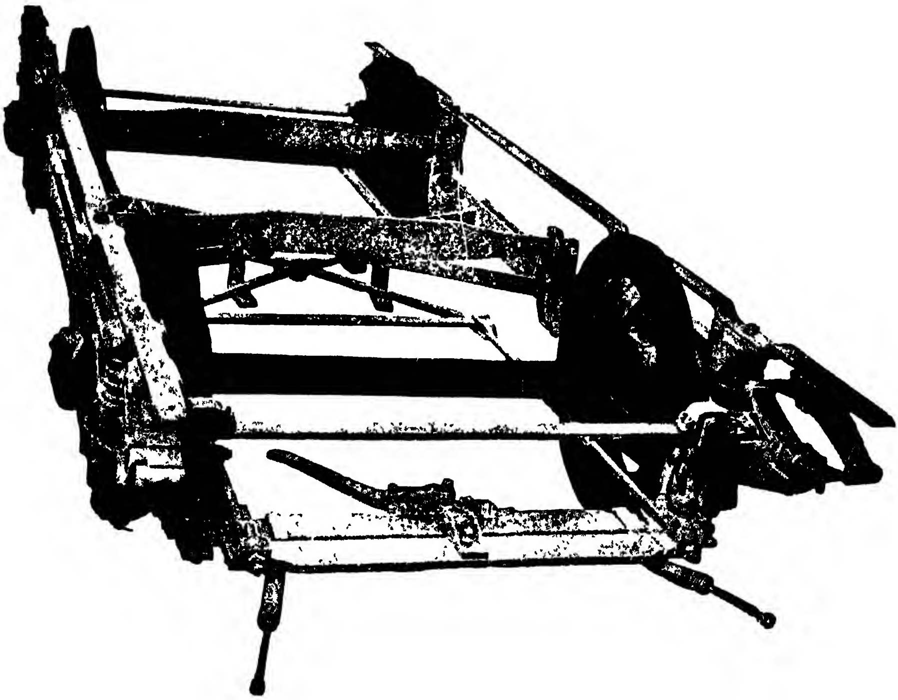


FIG. 258.—End View of Peckham Radial-axle Truck, showing swinging motor suspension-bar and brake gear (Brush Electrical Engineering Co.).

capable of lateral movement—is displaced slightly outwards, thereby causing the axles to take up a position approximately radial to the curve. The radiating action will, of course, be better at higher speeds than at low speeds, and the use of the special type of swinging link ensures that the axles will return to the normal position when the car leaves the curve.

The long swing-links will permit considerable radial movement of the axles to take place without the links assuming an excessive inclination, while the arrangement of the pins at the bottom of the links ensures that the car body will be held steady on straight track.

The brake gear is arranged to radiate with the axles by means of floating and equalizing levers, the supports for the brake-block links being carried on extensions of the motor suspension bars.

The truck is built with a wheel base of from 8 ft. to 12 ft., and is

FIG. 259.—Brill " Radiax " Radial-axle Truck.

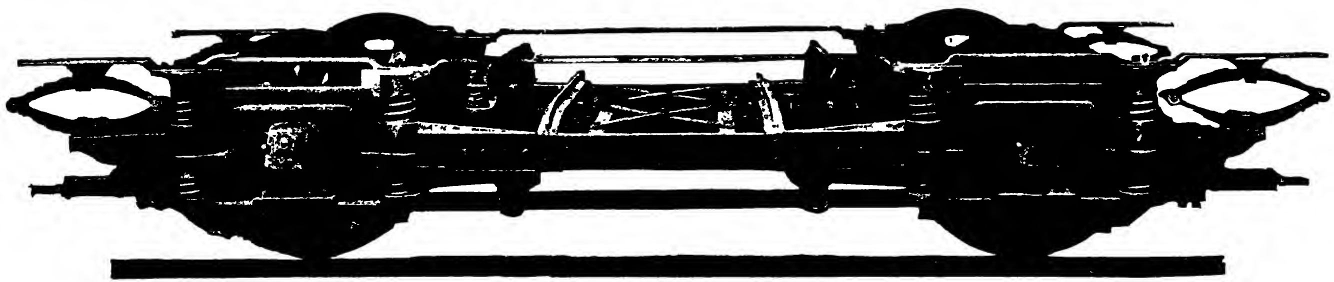


FIG. 260.—Peckham Radial-axle Truck (sub-truck type). (Brush Electrical Engineering Co.).

suitable for car bodies which do not exceed 36 ft. over the platforms. With a standard wheel flange and a $1\frac{1}{4}$ in. groove in the rail, the truck with the shorter wheel base will negotiate a curve of 29 ft. radius as satisfactorily as a rigid-axle truck with a wheel base of 4 ft. $1\frac{1}{2}$ in.

The **Peckham sub-truck type of radial-axle truck** is shown in Fig. 260. In this truck the axle boxes are fixed to two sub-trucks, which carry the motors and the brake gear. The main truck frame is carried on supporting frames (as in other Peckham trucks), which are suspended from the axle boxes by swing-links, the latter being hinged to short carriages, provided with roller bearings, on which the supporting frames are carried. Thus the supporting frames have a limited longitudinal movement as well as a transverse movement, so that the axles can adjust themselves to the curvature of the track. In order that the radial movement of the axles shall not be restricted by the swing-links, the latter are hung from swivel seatings on the top of the axle boxes.

The inner ends of the sub-trucks are each provided with radius links, which engage rollers fitted to the cross frames and located in the centre line of the main truck frame. The sub-trucks are also connected to the main truck frame at these points by springs, which provide the restoring force for returning the sub-trucks to their normal position.

On account of the radius links and the method of supporting the truck frame from the axle boxes, the sub-trucks are able to take up a radial position on curves of short radii. The minimum radius of curve which can be negotiated with the axles in the radial position depends on the wheel base of the truck and other features. With the present designs of Peckham radial-axle trucks, curves of 30 ft. radius can be negotiated by a truck with a wheel base of 10 ft., the axles being in the radial position.

Bogie trucks. Two types are adopted for electric traction, viz. (1) the maximum-traction truck (also called a single-motor truck), having wheels of unequal diameter—the use of which is exclusive to tramways—and (2) the equal-wheel bogie truck, which is principally used on railways and is described in Chapter XVI.

In the latter truck the load is supported on a bolster placed midway between the axles, and is distributed equally between them. Hence if only one axle is equipped with a motor, approximately one-half of the load on the bolster will be available for adhesion.* But if the load is supported nearer the driving axle, a larger portion of it will be available for adhesion. The practical limit is reached when about 75 per cent to 80 per cent of the total weight of the car (i.e. the car body, trucks, and electrical equipment) is placed on the driving axles, and trucks constructed on this principle are known as the **maximum traction type.** Trucks of this type, therefore, enable large bogie cars to be equipped with only two motors, provided that the gradients do not exceed about 1 in 15.

Maximum-traction, swing-bolster trucks. In all modern types of maximum-traction trucks the car body is supported on a "**swing bolster,**" and in some cases the pivotal point or swivelling centre is displaced from the centre of the bolster towards the driving axle. The radiation of the

* The load on the driving axle will also include one-half of the weight of the truck and the component of the weight of the motor which is not carried on the suspension springs.

driving wheels (that is, the transverse movement of the wheels relative to the car body when the car is rounding a curve) is thereby reduced. Hence if the pony wheels are of smaller diameter than the driving wheels

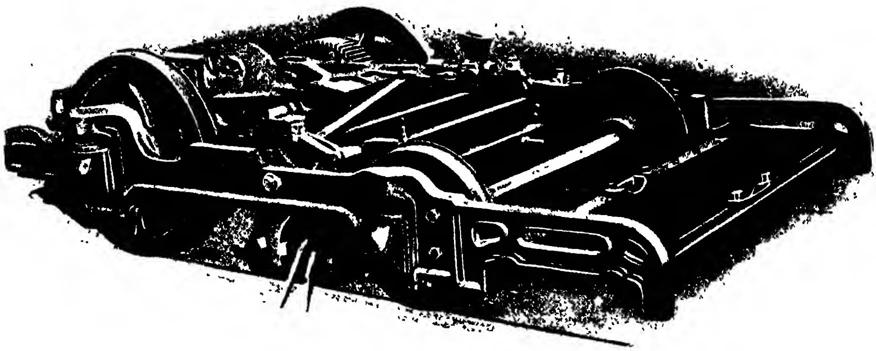


FIG. 261.—Maximum-traction Swing-bolster Bogie Truck, as adopted by the London County Council Conduit Tramways.

the side-sills of the car may be carried low, with a consequent reduction in the height of the platforms and floor.

A truck of this type, which has been standardized on the London County Council tramways, is illustrated in Fig. 261. The side frames are of cast steel, and are connected together by four channel sections, one at each end and two in the centre. The centre channels are called the

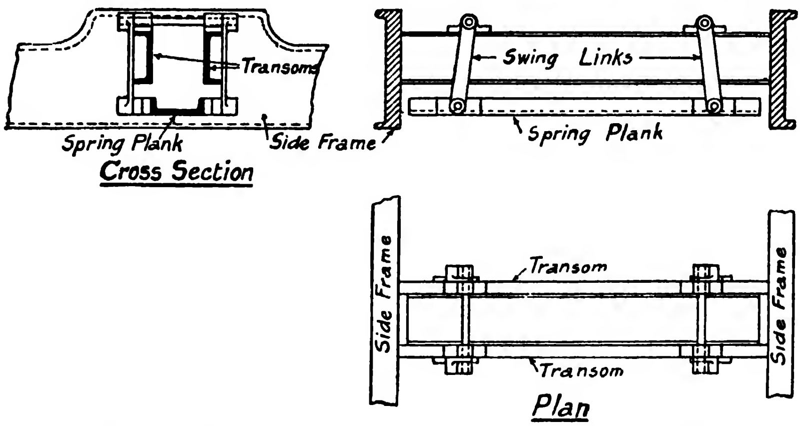


FIG. 262.—Arrangement of Transoms, Swing-links, and Spring Plank in Maximum-traction Swing-bolster Bogie Truck.

transoms, and are fixed thus :] [. Another channel section (arranged thus : ⌴, and called the **spring plank**) is suspended under the transoms by two pairs of swing links, as indicated diagrammatically in Fig. 262. These swing-links allow the bolster to swing slightly outwards when the car negotiates a curve, thereby relieving the car body and truck from strains which would otherwise be produced. They also give easier riding to the car.

The springs upon which the bolster is supported are carried by the spring plank, and the springs supporting the truck frame are carried on the top of the axle boxes. The cast-steel bolster is a sliding fit between the transoms, and performs the double function of supporting the car body and of transmitting thereto the thrust from the truck. The car body is not permanently fixed to the bolster, but is connected to it by a **king pin,** which forms the **swivelling centre** of the truck. In the present case the king pin is displaced from the centre of the bolster towards the driving axle, so that it is necessary to adopt a swivel- or radius-plate for the centre bearing. The upper portion of this swivel plate (which can be seen in Fig. 261) carries the king pin, and is fixed to the underframe of the car body, while the lower portion rests in a spherical seat on the bolster. The car body is also supported by **side bearings,** which are formed by a projection at each end of the bolster engaging bearing plates fixed to the underframe. In order to prevent excessive side swaying of the car, the oscillation of the bolster is limited by the suspension pins of the swing-links extending across the tops of the transoms.

The wheel base of the truck is 4 ft. 6 in., the centre of the bolster is 2 ft. from the centre of the driving axle, and the swivelling centre is displaced 1 ft. 5 in. from the bolster towards the driving axle.

On account of the restricted space between the bolster and the driving axle, the motor must be placed in the "outside" position, the suspension bar resting on springs which are carried on brackets fixed to the end frame. This position of the motor is a characteristic feature of all maximum traction trucks of the bolster type, and a little consideration will show that it results in a reduction of the load (due to the car body and truck) on the pony wheels. As the position of the bolster is governed by the diameter of the driving wheels, it is generally necessary to carry at least 40 per cent of the weight of the car body on each pair of pony wheels, and consequently there is always sufficient load on these wheels to compensate for the lifting action of the motor.

It will be observed in Fig. 261 that the side frames are fitted with two extensions, which are connected together by two steel channels. These extensions are only fitted to one of the trucks on a car, and are for the purpose of carrying the plough collector.

The truck is also equipped with a magnetic track brake, which is arranged to operate the wheel brakes in the manner described later. The wheel brakes, however, can be operated independently of the track brakes in the usual manner.

The **Brill 39 E swing-bolster, maximum-traction truck** is illustrated in Fig. 263. This truck differs in several features from the truck last described. Firstly, the pivotal point is at the centre of the bolster; secondly, there is no spring plank; and thirdly, the bolster is provided with a graduated spring system which gives easy riding at all loads.

The side frames are of forged steel, and rest on spiral springs placed on the top of the axle boxes. The transoms are of angle steel, and are bolted to gusset plates fixed to the upper chord of each side frame. Elliptical swing-links are carried from the side frames at each side of the transoms, and these links support the ends of semi-elliptic springs, from which the bolster is supported. In the earlier forms of this truck the bolster was fixed directly to these springs, but in the truck under

consideration a short spiral spring, in special caps, is interposed between each end of the bolster and the semi-elliptic springs. The caps—in which the spiral springs are placed—are about $\frac{3}{8}$ in. apart when the unloaded car body is in position. When the car is about half-loaded with passengers the spiral springs are compressed, so that the caps come into contact, thereby transferring the load entirely to the semi-elliptic springs.

The bolster is of cast steel, and is connected to the lower spring caps (which are fixed to the centre of the semi-elliptic springs) by links, thereby relieving the spiral springs from side thrusts and also preventing the semi-elliptic springs from twisting when the bolster swings over.

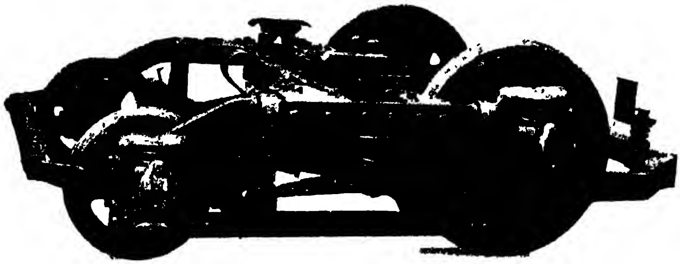


FIG. 263.—Brill "39 E" Maximum-traction Swing-bolster Bogie Truck.

The bearings for the king pin and car body are fitted to the top of the bolster, while to the sides are fitted chafing (or bearing) plates, which engage similar plates fitted to the transoms.

The truck is built with a 4 ft. 6 in. wheel base, the centre of the bolster being 1 ft. 11 in. from the centre of the driving axle. The diameter of the driving wheels may be from 30 in. to 34 in., while that of the corresponding pony wheels is 19 in. to 23 in. The weight of the truck (without wheels and axles) for standard gauge is 2750 lb.

The **brake gear for a maximum-traction truck** differs from that for a truck with a central bolster, in that *unequal pressures must be applied to the brake shoes on the driving and pony wheels*, the pressures being in the ratio of the loads carried on the wheels. In the truck under consideration this is accomplished by a differential lever system with brake beams for both sets of wheels, which ensures the alignment of the brake shoes on each pair of wheels.

The arrangement of the levers and brake beams is indicated in Fig. 264. The brake shoes for the driving wheels are suspended from brackets fixed to one of the transoms, while those for the pony wheels are suspended from brackets fixed to the upper chord of the side frames. The brake beams *B*, *C* are operated by a central lever *A*, to which is connected a pull rod *K* from a floating lever attached to the centre of the underframe, the pull rods from the brake spindles on the platforms being also connected to this floating lever, so that the radiation of the trucks does not interfere with the operation of the brakes. The central lever *A* is connected to the brake beam *B* by the link *D*, and its lower end is connected by the adjustable rod *E* to the differential lever *F*,

which has a fulcrum on the cross-bar G, fixed to the lower chords of the side frames. The upper end of the differential lever is connected to the pony wheel brake beam C. When a tension is applied to the pull rod K the lever A turns about the pin L and applies the brakes to the driving wheels. As soon as these brakes are applied the lever has a fulcrum at the pin M, and a force is transmitted through the rod E to the differential lever and brake beam C, thereby applying the brakes to the pony wheels.

Wheels. Two types of wheels are in use on tramways, viz. (1) the chilled cast-iron wheel (which is a relic of horse tramways), and (2) the steel-tyred wheel with a steel centre. In the first type the thickness of

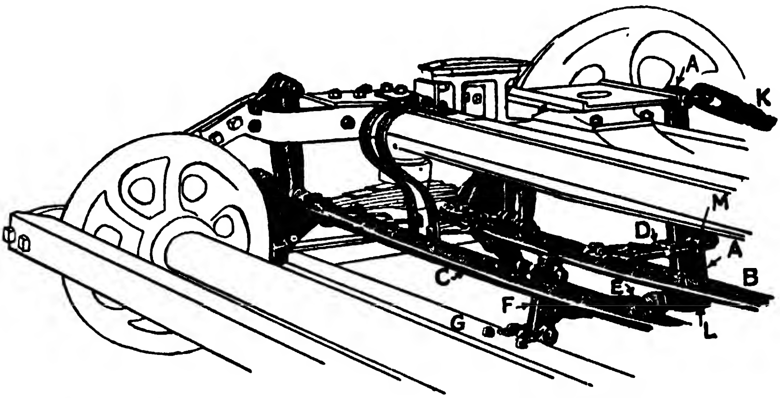


FIG. 264.—Arrangement of Brake Gear on Bril "39 E" Maximum-traction Bogie Truck.

the "chill" is about $\frac{3}{4}$ in., and the wheels must be scrapped when this amount of wear has taken place. The guaranteed life is 30,000 miles, but there are records of wheels of this type averaging 40,000 to 60,000 miles.*

The second type of wheel is made with the centre either of cast steel or of forged steel, and has the advantage that the centre seldom requires renewing. This wheel is more costly at the outset than the "chilled" wheel, but the average cost over a number of years will be lower. The tyres are usually 2 in. to $2\frac{1}{2}$ in. thick at the tread; they are shrunk on to the centres and secured in position by set-screws or retaining rings. The steel from which the tyres are manufactured is exceptionally hard, but at the same time it is tough and ductile, the tensile strength being approximately 50 tons per sq. in. With tyres $2\frac{1}{2}$ in. thick a wear of from $1\frac{1}{2}$ in. to $1\frac{3}{4}$ in. radially can be allowed, which will give a life of from 60,000 to 100,000 miles, the guaranteed life being usually based on a radial wear of $\frac{1}{8}$ in. for every 5000 miles. These figures, of course, will be affected by the curvature of the track, since,

* For some comparative tests on the durability of brake shoes and tyres see a paper (by Mr. W. J. Dawson) presented to the 1910 Annual Conference of the Municipal Tramways Association. See *The Electrician*, vol. 65, p. 1010.

if the curves are all in one direction, the tyres of the wheels on one side of the car will be worn at a greater rate than those on the other side.

The average weight of a chilled cast-iron wheel (30 in. in diameter) is 300 lb., while that of a steel-tyred wheel (31¾ in. in diameter) is 350 lb.

Until recently the standard diameter for driving wheels was 30 in. in this country, and 33 in. in America. But with the introduction of low floor cars, wheels of 26 in. diameter have become standardized, suitable motors for these wheels having been developed.

Position of pony wheels for cars with bogie trucks. In all the above types of maximum-traction trucks the running of the truck is satisfactory whether the pony wheels are leading or trailing. Since tramcars must be suitable for running in either direction, the trucks are arranged symmetrically about the centre of the car, with the pony wheels either towards the centre or towards the platforms. The latter position is standard for American practice,* and the pony wheels are arranged under the platforms, thereby giving a better support for these portions of the car. In this country, however, the space under the platforms is required for the life guards, and, unless the platforms are very long, the car body will be supported better with the pony wheels towards the centre of the car. Generally, the arrangement of the trucks will be influenced by the design of the underframe, and, in a given case, the trucks should be arranged to provide the best support for the car body and the platforms. These are probably the reasons for the apparent diversity of opinion among some car builders, in consequence of which there are numerous examples of cars with the pony wheels towards the centre and towards the platforms. In the case of conduit tramways, the plough must be supported from an extension of the truck frame (see Fig. 261), and under these conditions the trucks must be arranged with the pony wheels towards the centre of the car.

Brakes

The importance of brakes on an electric tramcar cannot be over-estimated, and they should be given quite as much attention as the electrical equipment. All cars must be equipped with hand brakes, in which the brake shoes act on the rims of the wheels, while cars which have to operate on steep gradients must be equipped also with track brakes. In the case of large tramway systems, operating through congested traffic, the maximum speed is fixed by statutory regulations, and is based on the brake equipment. Cars equipped with powerful and quick-acting brakes can, therefore, be run at higher schedule speeds than those not so equipped. This point is of the utmost importance on a system like the London County Council Tramways, where competing petrol motor omnibuses run over practically the same routes as the tramcars.

The principal **types of brakes** in use on tramcars are: (1) the wheel (or hand) brake, which acts on the wheels only; (2) the rheostatic electric brake, in which the motors are converted into generators and are loaded on rheostats, the brake being applied and regulated from the controller (see Chapter VIII, p. 180); (3) the mechanical track

* With the centre-entrance cars, the trucks have to be arranged with the pony wheels towards the centre of the car.

brake, applied by hand from hand wheels on the platforms of the car; (4) the magnetic track brake, with or without an attachment for operating the wheel brakes, the current for the excitation of the magnets being derived from the motors.

The air brake, although used extensively in America, has not been adopted in this country on account of the additional equipment required on the car. Moreover, the speeds and traffic conditions here do not warrant the use of this type of brake.

Wheel brake. The wheel brake, applied by hand, is a relic of the horse tramcars, with improvements introduced to obtain a greater braking force and a more rapid application of the brake. The pull rods

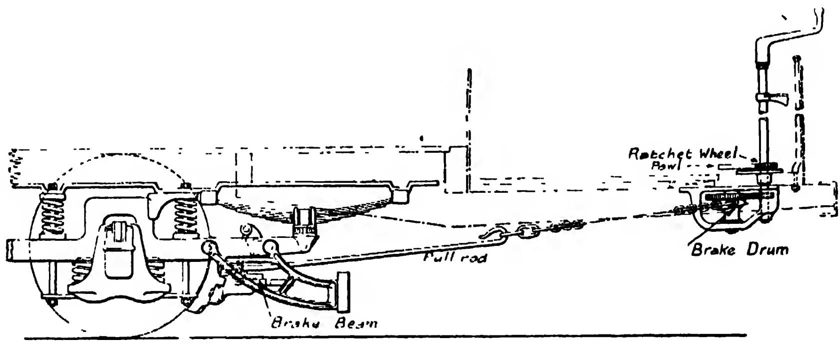


FIG. 265.—Arrangement of Platform Gear for Wheel Brake on Single-truck Car. (A Peacock quick-acting geared brake drum is shown.)

from the brake levers (p. 356) are connected to the brake drums on the platform operating gear by a short length of chain, as shown in Fig. 265. The brake is applied by winding this chain around the brake drum, unwinding being prevented by means of a ratchet wheel and pawl on the operating spindle.

The **Peacock quick-acting brake** has the drum in the form of a grooved cam B (Fig. 266), which is geared to the operating spindle A. The pinion and gear wheel of the operating gear are fitted with stops C, D, which are in contact when the brakes are "off" (see diagram X, Fig. 266). These stops prevent the brake drum from over-running when the brakes are released, and ensure that the drum is stopped in a position from which the recovery of the chain is most rapid. Thus during the application of the brakes all unnecessary winding is avoided, and the cam type brake drum ensures a quick action. The gearing enables a powerful braking effect to be obtained without excessive exertion from the motorman.

For cars weighing from 12 to 15 tons it is general practice to employ a gear ratio of 39/12, which, with the standard $10\frac{1}{2}$ in. operating handle, gives a leverage of 22 between the handle and the chain. With an effort of 50 lb. applied to the handle, the resulting tension (corrected for friction) in the brake chain is 983 lb.

Track brakes. The **mechanical track brake*** is of the slipper type, and usually consists of one or more pairs of wooden blocks, which are pressed on to the track rails by means of levers, or screws, operated from a hand wheel on the platform. This brake is intended for use on steep gradients, and utilizes a portion of the weight of the car as the braking force. The wheel brakes can, of course, be applied at the same time, but in order to render these brakes operative it is necessary to design the hand wheel and levers of the track brake so that sufficient weight is carried on the wheels to prevent them skidding when the brakes are applied.

The **magnetic track brake** consists of two or more electromagnets, flexibly suspended so as normally to clear the track rails, and which, when energized are attracted to the track rails; the drag or thrust of the magnets being transmitted to the truck frame, and, in some cases, to the shoes of the wheel brakes. The magnets are wound for series excitation and are connected in series with the braking rheostats (Fig. 122). In some very special cases compound excitation is provided, the shunt excitation being supplied from the trolley wire.

The excitation of the brake magnets from the car motors is considered to be more reliable than obtaining the excitation from the trolley wire, as the brake is thereby rendered independent of the generating station or the position of the trolley wheel. On the other hand, the wheels must not be locked by the misuse of the hand (wheel) brake.

When the wheel brakes are actuated by the track brakes, a combination of three brakes is obtained, viz. (1) a track brake, (2) a wheel brake, and (3) an electric brake, produced by the retarding torque due to the motors acting as generators, and in consequence very high retardations are possible. For example, under emergency conditions a retardation of 12 ft. per sec. per sec. can be obtained. For service applications, however, the retardation should be limited to from 2 to 3 ft. per sec. per sec.

Since the action of the brake is dependent upon the revolution of the driving wheels, means must be taken to prevent these skidding when emergency applications are made.

The **electromagnets** are of the bi-polar type with elongated pole faces, which are arranged longitudinally with the rail head and a short distance apart. A typical magnet is illustrated in Fig. 267. The body of the magnet is of cast steel, and the renewable pole faces are of soft steel. The excitation is supplied by a single coil, which is enclosed in a watertight metal case.

The magnetic circuit is transverse to the rail head, so that the flux is not limited by the section of the rail head. The vertical force between the magnet and the rail can, therefore, be arranged to suit the class of car by altering the length of the pole faces.

The design of the magnet is such that a large vertical pull can be obtained with a moderate exciting current. For example, in one size of magnet a pull of 2 tons is obtained with an exciting current of 20 amperes, and a pull of nearly 1 ton is obtained with a current of 5 amperes. It is

* See *The Tramway and Railway World*, vol. 29, p. 229, for particulars of a mechanical track brake (for centre-slot conduit tramways) which has been adopted by the London County Council Tramways on exceptionally steep gradients (1 in 10).

For further particulars of Mechanical Track Brakes see *The Tramway and Railway World*, vol. 35, p. 355.

evident therefore that this brake, when combined with the wheel brakes in the above manner, can be used as a service brake without producing an excessive temperature rise of the motors. The increased retardation will then allow of an increase in the schedule speed, and in many cases it will be possible to operate at a higher maximum speed (due to the more efficient braking equipment) than when the hand brake is used for service stops.

The magnet is suspended from the side frame of the truck by spiral springs, which are adjusted so that the pole faces are about ¼ in. above the rail. The magnets on opposite sides of the truck are connected together by cross bars, which are bolted to projections on the inner pole

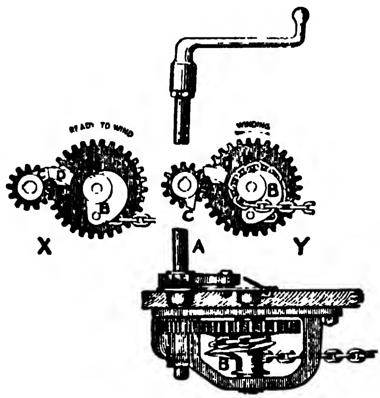


FIG. 266.—Peacock Quick-acting Brake.

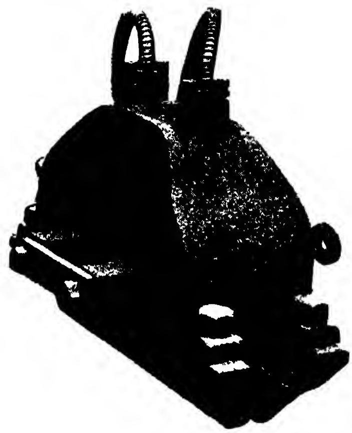


FIG. 267.—Magnet of Track Brake. (B.T.-H Co.)

pieces: two other projections on the outer pole pieces engage the tails of thrust brackets fixed to the side frames (Fig. 268).

In the **Metropolitan-Vickers magnetic track brake** the magnet is arranged to operate the wheel brakes in addition to transmitting its thrust to the truck frame. The attachments for operating the wheel brakes are shown in Figs. 268, 268A.

When emergency applications are made at high speeds there is a possibility of the wheels skidding if the brake is applied too quickly, as under these conditions the motors will build up to a high voltage and produce a large current in the brake circuit.*

The heavy application of the wheel brakes, combined with the large retarding torque on the motors, will produce a braking force which may be in excess of the maximum value permissible. Under these conditions the wheels will skid, thereby rendering the brakes ineffective. In order to avoid this, a skid-proof attachment has been developed which consists of solenoid-operated switches connected in the brake circuit so as

* The resistance in the brake circuit at each notch of the controller is the same at all speeds, and must be arranged so that the brake is effective at low speeds (e.g. 2 ml.p.h.).

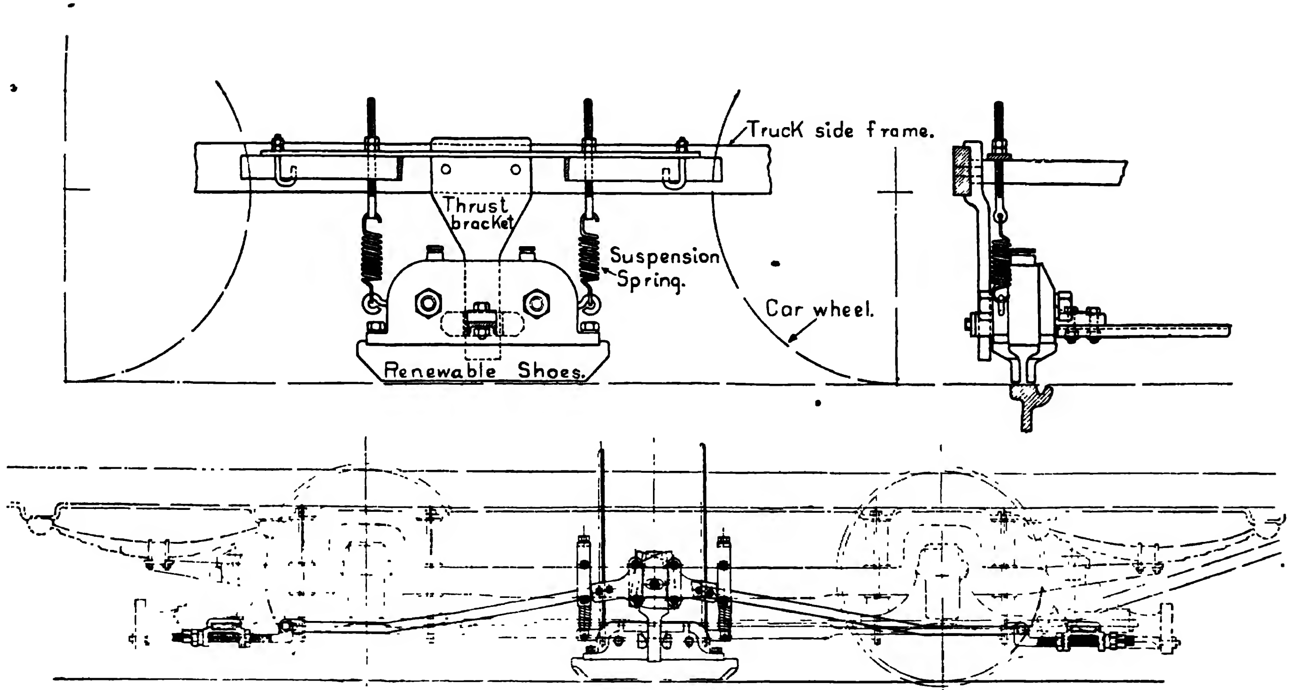


Fig. 268.—Arrangement of Magnetic Track Brakes on Single Trucks.
Upper diagram, ordinary arrangement (B.T.-H. Co.), lower diagram, attachment for operating wheel brakes (Metropolitan-Vickers).

to connect resistances in parallel with the fields of the motors when the current in the brake circuit exceeds certain values.

Magnetic track brakes may also be fitted with **mechanical operating gear** for pressing the magnets on to the track rails. This feature may be desirable when steep gradients have to be negotiated, as the brake can then be applied before the car starts the descent. Moreover, the brake is operative if there should be an open circuit or a bad connection in the brake circuit.*

Vertical pull between magnet and rail. The force of attraction, or "pull," of any magnet on its armature is given by the fundamental equation $f = B^2A/8\pi$, where B is the flux density at the pole face (expressed in C.G.S. units and assumed to be uniform), A is the area (in square cms.) of the pole faces in contact with the armature, and f the force of attraction in dynes.

Converting f into tons weight, and A into square inches, we have (tons) $= (B^2A/3{\cdot}9) \times 10^{-9}$. For $B = 15{,}500$ (which corresponds to a

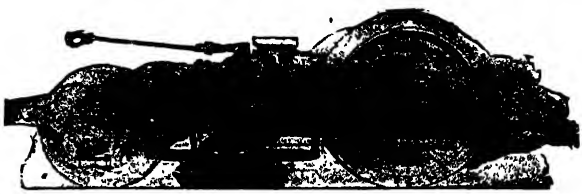


FIG. 268A.—Metropolitan-Vickers Magnetic Track Brake Fitted to Bogie Truck.

moderate saturation with cast steel) $f = 0{\cdot}0616$ tons for each square inch of pole face area. Thus, at this flux density, the pressure between the magnet and the rail will be 138 lb. per sq. in.

II. ROLLING STOCK FOR RAILLESS ROUTES

Railless cars, or trolley omnibuses, follow the general design of petrol-propelled omnibuses. The body (which may be of either the single-deck or double-deck type) is mounted upon a four- or six-wheeled chassis, of which the front wheels are provided with steering gear and the rear wheels are driven through a differential gear.

The choice of body is governed by conditions somewhat similar to those governing the choice of a tramcar, but in the present case the wheel base of the chassis is not restricted by the curvature of the route.

TROLLEY-OMNIBUS BODIES

Typical single-deck omnibuses are illustrated in Figs. 269, 270. The vehicles shown in Fig. 269 are each designed for two-man operation (i.e. driver and conductor), but the vehicle shown in Fig. 270 is designed for one-man operation, the fares being collected by the driver, and the entrance being at the front of the vehicle. In both this vehicle and those (Fig. 269) having a centre entrance, an emergency exit is provided at the rear.

* Some serious accidents have happened due to the failure of the brake from these causes. See Board of Trade reports in *The Electrician*, vols. 58, p. 102; 61, pp. 402, 913.

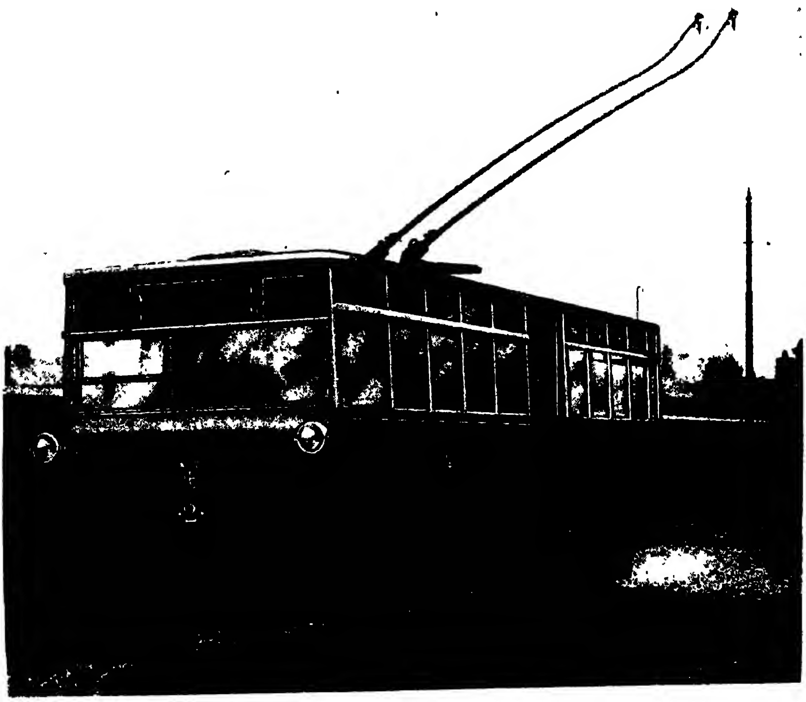


FIG. 269.—Single-deck Centro-entrance Trolley-buses, showing Alternative Types of Bodies and Trolley Standards. (B.T.-H. Co.)
The upper Fig. shows also the overhead construction at a terminal loop.

FIG. 270.—Single-deck One-man Trolley-bus. (Brush Electrical Engineering Co.)

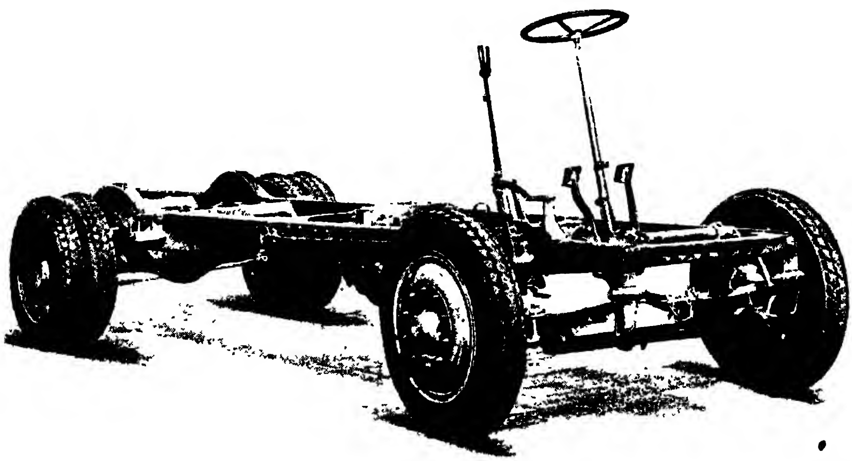


FIG. 271.—English-Electric-Leyland Trolley-bus Chassis.

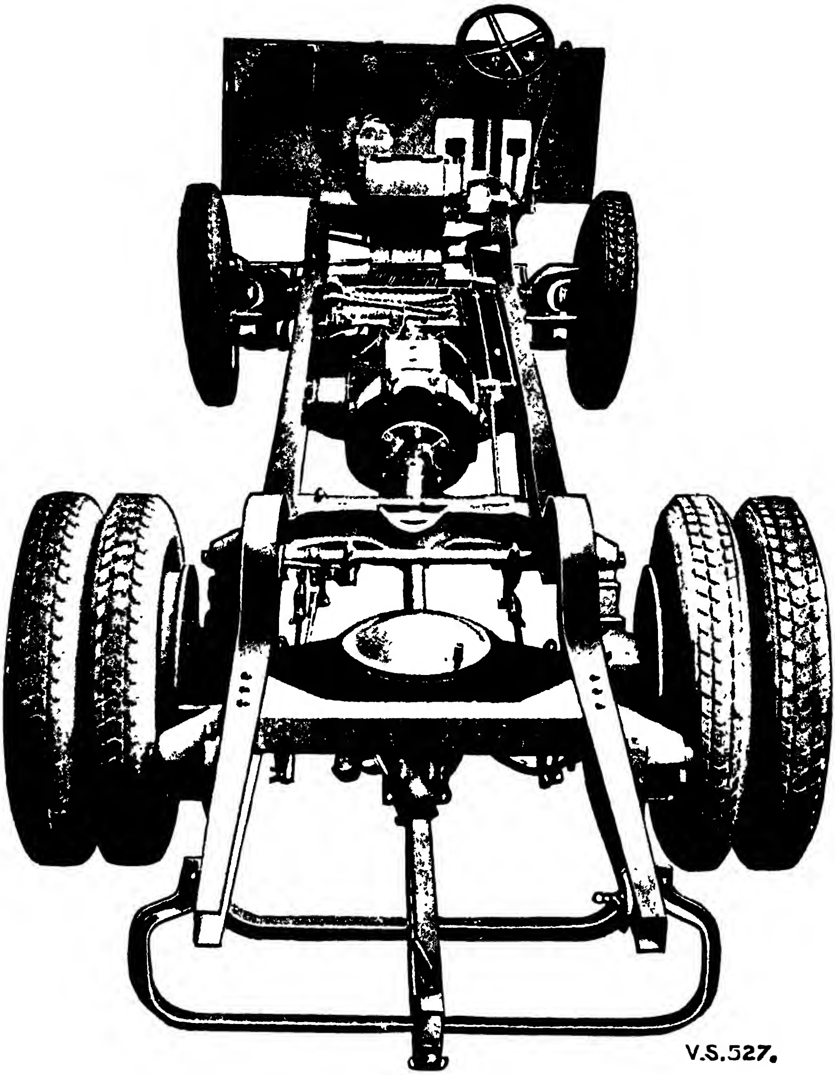


FIG. 272. Garrett Trolley-bus Chassis.

The body framing is constructed of oak and ash, and is reinforced by steel sections and plates. The facing strips, plating, and panelling are of either thin sheet steel or aluminium.

TROLLEY-OMNIBUS CHASSIS

The chassis follows the general layout of that for a petrol-propelled omnibus, i.e. the propelling equipment is fixed to the chassis frame between the axles, and the power is transmitted to the rear axle through flexible couplings and a cardan shaft.

Typical chasses are shown in Figs. 271, 272, 273.

The **frame** is of pressed steel with cast-steel brackets for carrying the springs, brake gear, and other fittings. The springs at both front and rear are of the semi-elliptic type. The ends of each spring are secured to the

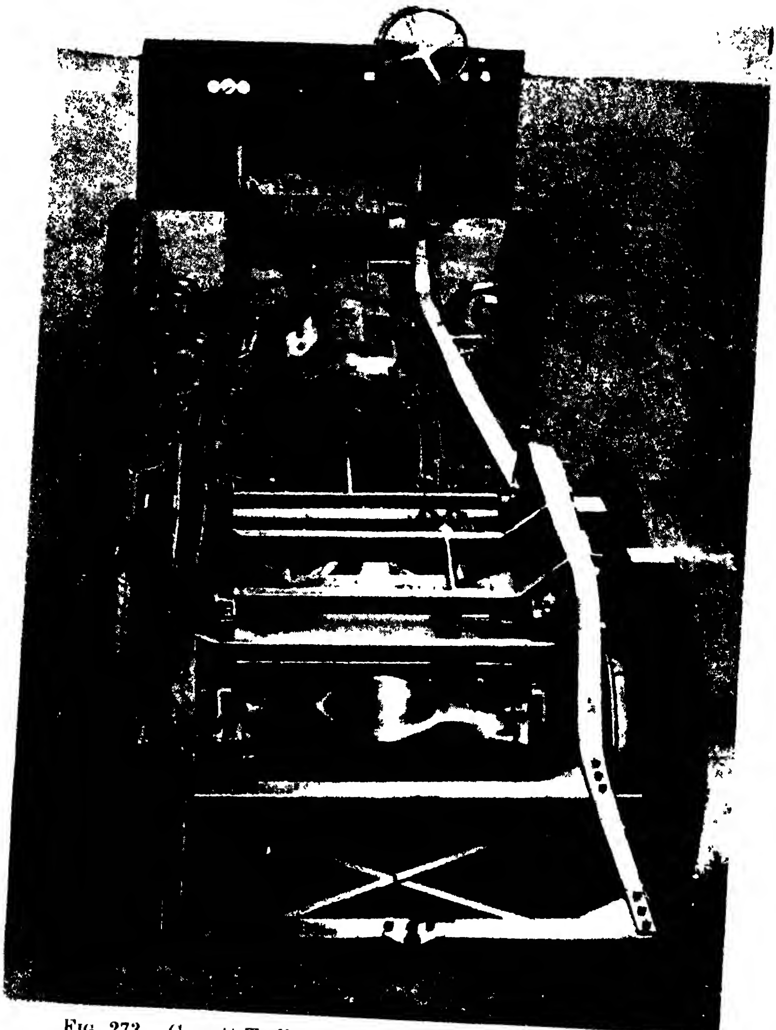


FIG. 273.—Garrett Trolley-bus Chassis with Two Driving Axles (Four-wheel Drive).

frame by suitable shackles, and the centre of each is bolted to the appropriate axle.

The **front axle** is a steel stamping, of I section, having forked ends which carry the swivel pins of the wheel hubs.

The **rear axle** is of the "full floating" type (i.e. the axle shafts are

subjected only to torsion, the load being carried by a separate casing concentric with these shafts). A cross-section of a portion of a typical rear axle is shown in Fig. 274. The central portion, *A*, of the axle casing contains the combined worm-reduction and differential gear. The bevel pinions of the latter are arranged inside the worm wheel, and the bevel wheels are carried in ball bearings located in the axle casing. The axle shafts, *B*, have their inner ends fitted to the bevel wheels and their outer ends fitted to the wheel hubs, *C*, which are carried in roller bearings fitted to steel tubes, *D*. These are fixed to the end portions, *E*, of the axle casing, which also carry the operating spindles and other fittings for the brake shoes. The driving worm, *F*, is carried in ball and roller

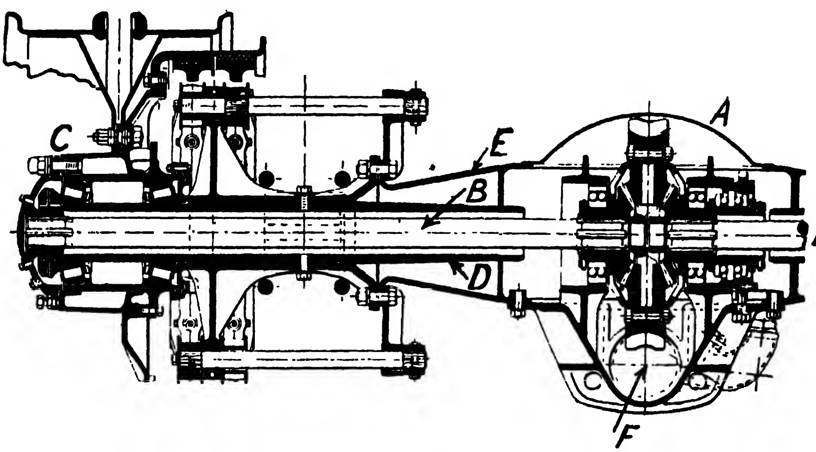


FIG. 274.—Rear Axle of Garrett Trolley Bus.

bearings in the lower part of the central casing, *A*, and its driving end is connected by a universal joint to a tubular propeller shaft, the forward end of which is flexibly coupled to the driving motor. The tractive force of the driving wheels is transmitted to the frame by the semi-elliptic suspension springs.

Location of electrical equipment. The general arrangement of the motor and control equipment is shown in Figs. 272, 273. In each case a single double-commutator motor is employed. The controller is of the pedal-operated type and is located at the forward end of the vehicle, adjoining the dashboard. On the latter are mounted the circuit breakers for the power circuits, and the switches and fuses for the lighting circuits. The starting rheostats are suspended from the chassis.

Wheels. These are of either the disc or the spoked types, and may have either solid rubber or low-pressure pneumatic tyres. Examples of both are shown in Figs. 269, 270.

Brakes. Statutory regulations require each vehicle to be equipped with two independent mechanical brakes. These are of the expanding type, with internal friction lined brake shoes acting upon steel drums

fitted to the wheel hubs. When brakes are fitted to all wheels, duplicate brakes are fitted only to the rear wheels. Hence one set of brakes is effective on all wheels and the other set is effective only on the rear wheels.

Usually one set of brakes is pedal operated and the other is hand operated, but many of the larger vehicles have pneumatic operating gear in addition to the pedal operating gear, the compressed air being obtained from a reservoir and the brake valve being pedal operated. The reservoir is supplied with compressed air by a small motor-driven compressor, which is controlled automatically, by a governor or pressure regulator, in the same manner as the larger compressed-air brake equipment on trains. The brake cylinders are of the diaphragm type, the diaphragm operating a push rod connected to the brake lever. The application valve supplies air direct from the reservoir to the brake cylinders, and is so designed that the air pressure in the brake cylinders is proportional to the depression of the operating pedal. The brake is released when the pedal is released.

With single-motor vehicles provision is usually made for electric (rheostatic) braking, but no such provision is made on two-motor vehicles with series-parallel control.

CHAPTER XVI

ROLLING STOCK FOR ELECTRIC RAILWAYS

(MOTOR COACH TRAINS)

Advantages of motor coach trains. The traffic requirements of urban and suburban railways involve the running of frequent trains at relatively high schedule speeds (for this class of service), together with facilities for (1) varying the composition of the trains to suit variations in traffic density; (2) getting the trains into and out of the terminal stations in the minimum time and with a minimum number of signal and train movements. These conditions can best be satisfied by the use of motor coach trains, which possess a number of advantages over locomotive hauled trains for urban and suburban service. Thus—

1. Since the passenger coaches are equipped with motors, the whole, or a large portion, of the train weight is available for adhesion, and a large number of driving axles are available. The loading on the permanent way due to a train is more uniform than in the case of a locomotive-hauled train (which would necessitate the use of a very heavy locomotive).

2. The trains can be made up to suit variations in traffic density with a minimum of shunting operations.* If the train weight per motor is maintained constant, the trains for light and heavy traffic will be able to maintain the same schedule speed with the same specific energy consumption.

3. The capacity of a terminus (expressed in terms of passengers per hour) is greater with motor coach trains owing to fewer signal and train movements being necessary, and the absence of docks or platform sidings which would have to be provided for locomotives.

Adhesive weight. In trains made up wholly of motor coaches and all axles equipped with motors, the adhesive weight is equal to the total train weight. On many railways in this country, however, it is the practice to operate one motor coach with one, two, or three trailer coaches as a *train unit*, and to run the service with trains made up of one unit, or of two or more units coupled together, as demanded by the traffic. In these cases the adhesive weight is equal to the total load on the axles which are equipped with motors. It should be at least 25 per cent of the total train weight (generally it is from 33 per cent to 50 per cent), and, to avoid slipping of the driving wheels under unfavourable conditions of weather, the total accelerating tractive effort should not exceed

* A striking example of the rapidity with which electric trains can be made up at a terminus has been given by Mr. J. Shaw (General Manager of the Mersey Railway) in a paper entitled "The Equipment and Working Results of the Mersey Railway under Steam and Electric Traction" (*Minutes of Proceedings of the Institution of Civil Engineers*, vol. 179, p. 19).

In the paper it is stated that the trains are allowed three minutes at the termini, during which interval any alteration in the make-up of the train has to be done. The average time for making up a train is two minutes, which includes shunting and coupling of brakes and electric connections.

about 15 per cent of the adhesive weight. The adhesive weight and total train weight of some typical motor coach trains are given in Table X, while further particulars of the motor coaches are given in Table XI (p. 412).

COACHES

Types. Two types are in use, viz. (1) the compartment type with side doors– similar to the rolling stock on our steam railways and (2) the saloon type of coach or car* with central and end doors. The latter type of stock was introduced for the early electrifications in this country, and it is the only type permissible for deep-level underground (or tube) railways. Although there exists a considerable difference of opinion among railway engineers as to the advantages of the two types of stock, nevertheless the saloon type, in virtue of its better facilities for the distribution of the passengers when entering the train, is more suitable for urban service with dense traffic than the compartment type. For longer distance suburban traffic, however, the compartment type of coach is generally preferable.

Limitations to dimensions. The maximum length and width of a coach which can be used on a given line is determined by the lay-out of the track (which affects the clearance between passing trains), the loading gauge, and the size of the tunnels. When sliding or inwardly opening doors are adopted -as in the saloon type of coach—the clearance between passing trains can be made smaller than that when outwardly opening side doors are used.

The length of trailer coaches for express service on the principal steam railways in this country varies from 50 ft. to 75 ft., while the width varies from 8 ft. to 9 ft. 3 in.

The largest electric coaches in this country (viz. those in service on the Liverpool-Southport section of the London, Midland and Scottish Railway) have a length of 60 ft., with a width of 10 ft. They are of the end-door saloon type, with transverse seats, a central corridor, and seating accommodation for 100 passengers. Each of the transverse seats on one side of the corridor is arranged to accommodate three passengers, while on the other side of the corridor two passengers are accommodated on each seat. The large width of the coach has enabled this arrangement of seats to be adopted with a corridor 2 ft. wide, whereas for a 9 ft. coach and the same width of corridor it would have been possible to seat only four passengers cross-wise, thereby reducing the seating capacity to 82. The increase in the weight of the coach, due to the increase in width. is only that of the floor, roof, and extra seats, and, for the 60 ft. coaches under consideration, is of the order of 15 cwt., or about 93 lb. per extra seat. If the increase in the seating capacity had had to be provided for by additional coaches to the train, the weight would have been of the order of 5 cwt. per extra seat.†

* The saloon type of coach, with end doors, is the standard type of passenger rolling stock in America, where all classes of rolling stock are designated as "cars." The term "car" is used to some extent in this country in connection with electric trains, particularly when these are of the saloon type.

† See "The Design of Rolling Stock for Electric Railways," by H. E. O'Brien (*Journal of the Institution of Electrical Engineers*, vol. 52, p. 445). This paper contains some interesting and valuable data on rolling stock.

TABLE X

Adhesive Weights of Typical Motor Coach Trains on British Railways

Railway.	Weight of one Motor-coach without Passengers.	Number of Motors per Motor-coach.	Weight of one Trailer-coach without Passengers.	Number of Passengers.		Composition of Train.	Total Weight of Train.		Adhesive Weight of Train.		Ratio—Adhesive Weight to Total Weight.	
				Motor-coach.	Trailer-coach.		Without Passengers.	With Full Number of Passengers.	Without Passengers.	With Full Number of Passengers.	Without Passengers.	With Full Number of Passengers.
	Tons.		Tons.				Tons.	Tons.	Tons.	Tons.		
Metropolitan District	33·89	2	22	44	48	4M, 4T	223·56	246·56	82·76	88·26	0·37	0·358
Metropolitan (Saloon stock)	46·6	4	22	37	50	2M, 5T	204	250	99·2	101·2	0·45	0·4
Metropolitan (Compartment stock)	39	4	20	30	70	2M, 5T	178	214	78	84	0·44	0·39
,, ,,	53·8	4	24·5	50	90	2M, 5T	234	283	107·6	116·6	0·46	0·41
London, Midland & Scottish (1)	54	4	28(T), 30(DT)	48	55(T), 60(DT)	1M, 1T, 1DT	112	123	54	57	0·482	0·463
,, ,, ,, (2)	56	4	28(T), 30(DT)	84	100(T), 96(DT)	1M, 1T, 1DT	114	131	56	61·25	0·491	0·467
,, ,, ,, (3)	54	4	29	74	96(3rd), 72(1st)	2M, 3T†	195	220	108	118	0·554	0·536
,, ,, ,, (4)	50·5	4	26·1	80	103(3rd), 76(1st)	2M, 2T*	153·2	174·4	101	111	0·659	0·637
						2M, 3T†	179·3	207	101	111	0·563	0·537
,, ,, ,, (5)	67	4	26·1	80	103(3rd), 76(1st)	2M, 3T†	212·3	240	134	144	0·631	0·601
,, ,, ,, (6)	53	4	28(T), 30(DT)	84	100(T), 96 (DT)	1M, 1T, 1DT	111	122	53	56	0·478	0·459
Southern Railway	39·5	2	26·3‡	80	90	4M, 4T	261	305	105·5	113·5	0·405	0·372
						3M, 4T	154·67	172·3	61·8	64·6	0·399	0·375
London Electric (tube) Railways	29·29§	2	16·7	30	48	2M, 4T	125·4	138·9	41·2	43·07	0·328	0·31
						2M, 2T	92	101·7	41·2	43·07	0·448	0·423

* Including one first-class trailer and one third-class trailer. † Including one first-class trailer and two third-class trailers. § A "train unit" consists of two motor-coaches and one trailer-coach. ‡ Heaviest trailer coach in use.

Reference to London, Midland & Scottish trains: (1) Euston–Watford Saloon Stock; (2) Euston–Watford Compartment Stock; (3) Manchester–Bury Saloon Stock; (4), (5) Liverpool–Southport Saloon Stock; (6) Liverpool–Southport Compartment Stock.

Construction. In the design of rolling stock for urban and suburban railways it is important to reduce the weight by the use of suitable materials, as unnecessary weight not only increases the energy consumption but also leads to increased maintenance costs when the whole of the equipment is considered. Of course, if the stock is built too lightly it will not be sufficiently strong to withstand the stresses due to high acceleration and braking, and in this case the maintenance costs will be high. But the use of aluminium and steel of high tensile strength will enable the weight to be reduced without sacrificing strength. With saloon coaches constructed of steel sections and sheets the sides of the body may be combined with the sole-bars of the underframe, thereby allowing the latter members to be reduced in section. This type of construction, although somewhat heavier than the standard wooden construction of similar dimensions, has a considerably lower maintenance cost than the latter.*

The construction of coaches for operating on surface electric railways usually follows the general practice for steam rolling stock, the principal exceptions being the underframes of the motor coaches, and the provision of driving compartments in the motor and trailer coaches.

The design of the **underframe for a motor coach** will be influenced by the type of coach, the method of control, and the disposition and weight of the control apparatus, auxiliary apparatus, etc. In multiple-unit trains the control and auxiliary apparatus may be located either in a compartment at one end of the coach or under the coach between the bogies. As the total weight of the control apparatus for a coach equipped with four direct-current motors may be of the order of $3\frac{1}{4}$ tons, the disposition of this apparatus must be carefully considered in the design of the underframe.

In the majority of cases the underframe is constructed of steel sections. The principal longitudinal members are of channel section, and are connected together by cross-bars and end frames (the latter being called "**head stocks**") to which the buffing and draw-gear is attached. The outer longitudinal members (called "**sole bars**") are fitted with adjustable truss rods,† which carry the tension component of the stress produced by the bending moment, while the compression component of the stress is carried by the channels. The centre pins, centre bearings, and side-bearing plates are fitted to cross channels, which, for a motor coach, have to be specially reinforced and braced to the sole bars and head stocks. In some types of underframes these channels are replaced by steel castings (called "**body bolsters**"). When the control apparatus is located in the coach body, the sole bars and longitudinal members are braced by diagonal bracings, but these have to be omitted when the control apparatus is fixed to the underframe. The cross-bars must then be supplemented by gusset plates.

The above types of underframes are adopted for rolling stock running on suburban railways, when the dimensions do not have to conform to

* See "The Design of Rolling Stock for Electric Railways," by H. E. O'Brien (*Journal of the Institution of Electrical Engineers*, p. 455).

† The truss-rods are adjusted to give a slight upward deflection, or camber, to the sole-bars when the coach body is unloaded and in position on the trucks. Truss-rods are not required on steel cars in which the sides and sole-bars are designed to form plate-girders.

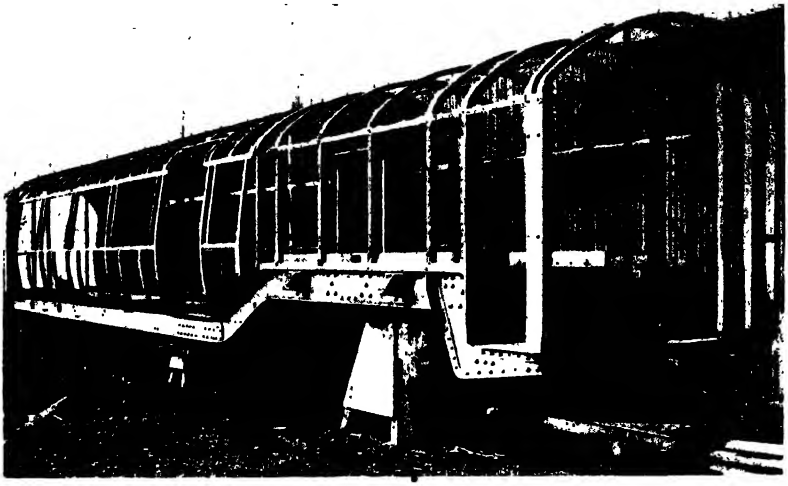


FIG. 275.— Centre-entrance Motor-car in course of construction at the Brush Electrical Engineering Co.'s Works. View from driving end. The raised floor of the control compartment should be noted. The floor of the driving compartment is on the same level as that of the passenger compartment.

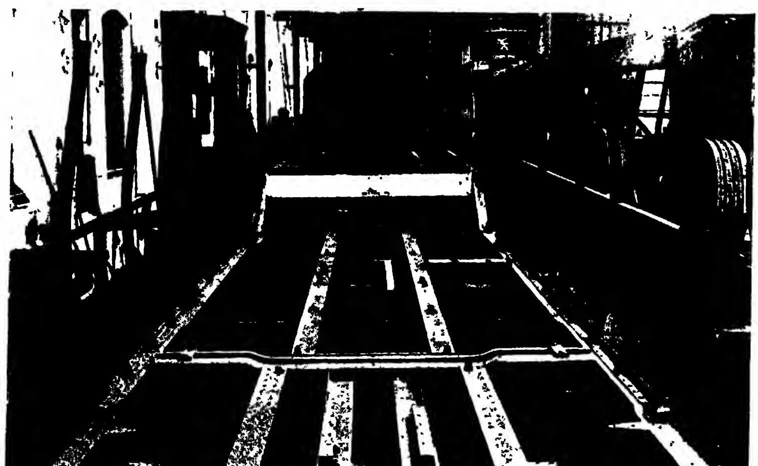


FIG. 276.—Underframe of Centre-entrance Motor-car in course of construction at the Brush Electrical Engineering Co.'s Works. View from trailer end.

a restricted loading gauge. In the case of **tube railways,** however, the loading gauge is much below that of surface railways on account of the limited diameter of the tunnel. For example, in the majority of the London tube railways the internal diameter of the tunnel (for straight single track) is 11 ft. 8¼ in., while the height from the track rails to the top of the tunnel is 9 ft. 11½ in. The rolling stock on these lines is of the saloon type, with end platforms and collapsible gates. The cars are built of steel, and the underframe is incorporated with the body, thereby resulting in a light construction for the former.

Views of a motor-car in course of construction at the Brush Electrical Engineering Co.'s works are shown in Figs. 275, 276, which show clearly the arrangement of the various members of the steel underframe and the body framing.

Trucks

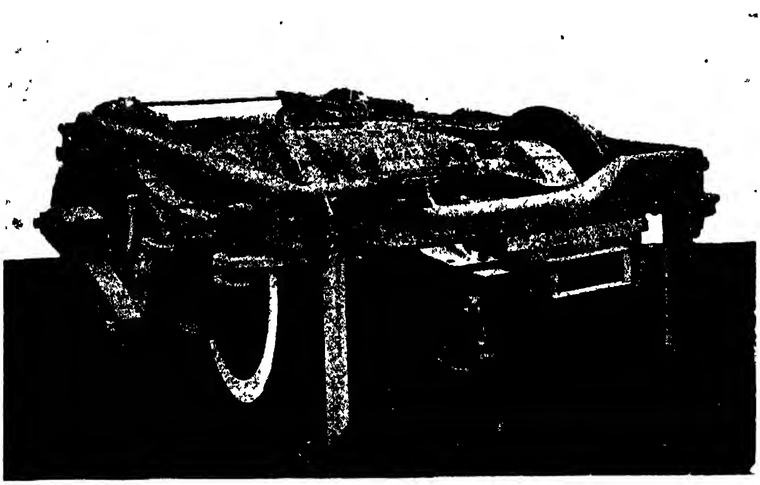
The trucks in use on the passenger rolling stock of railways are usually of the four-wheel bogie type with a central bolster, although in some cases (such as for dining cars, sleeping saloons, and drawing-room (Pullman) cars) a six-wheel bogie is adopted. The trucks for motor-coaches are, in general, of similar design to those for trailer coaches, except that the former are of heavier construction to withstand the greater stresses to which they are subjected. In this case, however, only four-wheel bogies are adopted, and it is general practice to equip both axles with motors. Since the curves on a railway are generally of fairly large radius, the wheel base of the trucks can be made much greater than the values adopted on tramways; and, in practice, a wheel base of from 6 ft. to 10 ft. is adopted, which allows the motors to be placed in the "inside" position (i.e. between the transoms and the axles).

Motor-trucks can be divided broadly into two classes, according to the spring system adopted between the truck frame and the axles. Thus (1) the truck frame may be supported on the axle boxes through laminated springs (Fig. 277), or (2) the truck frame may be supported on spiral springs carried on equalizing bars, the ends of which are supported directly on the boxes (Fig. 278). In each type of truck the bolster is supported on springs carried by the spring plank, which may be of either the swinging or the rigid type, the former being the more general for railways operating at moderate speeds.

Trucks of the first class (which may be called **non-equalized trucks**) are practically standard for all British railways, while trucks of the second class (which are called **equalized trucks**) are largely used in America and are only used to a limited extent in this country. This type of truck has superior riding qualities to the non-equalized type on poor track, but with the excellent track construction on our larger railways the riding qualities of the non-equalized truck are quite satisfactory. Moreover, the equalized truck is not only heavier and more costly to maintain than a non-equalized truck of equal wheel base, but it is subjected to a tilting action during braking—the forward end of truck being depressed and the rear end raised—this action being greatest when outside hung brake shoes are used.*

* For a full discussion of the forces produced during braking, see a paper on "Railroad Car Braking," by R. A. Parke (*Transactions of the American Institute of Electrical Engineers*, vol. 20, p. 235).

(a)



(b)

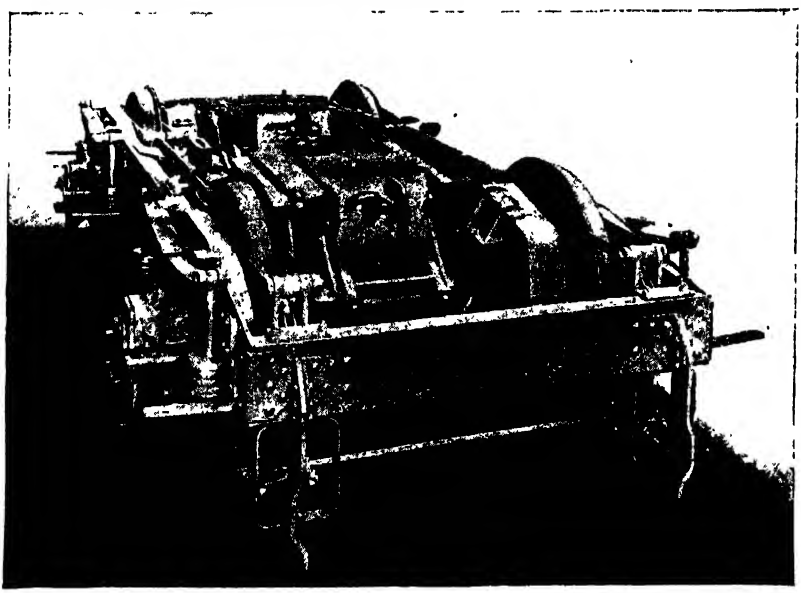


FIG. 277.—Types of British Non-equalized Motor-truck with motors and collector shoes in position.

(*a*) Truck with inside-hung brake shoes, one brake shoe per wheel; (*b*) truck with two brake shoes per wheel. (B.T.-H. and English Electric Co.'s equipments.)

In view of the large forces to which a motor-truck is subjected (the truck having to perform the work of a tractor in addition to carrying and guiding the car body), the frame must be very rigid and must be sufficiently braced to maintain its "squareness" under all conditions. As the only means of bracing the side frames is by the transoms and the end frames, these members must be liberally designed, and must be reinforced by gusset plates at the connections to the side frames. The gusset plates and diagonal bracing between the side frames, end frames, and transoms are shown very clearly in Fig. 279, which refers to a motor-truck with single-phase motors.

The frame of a non-equalized truck may be constructed of steel plate and rolled sections, of pressed-steel plate, or of cast steel; while the frame of an equalized truck may be constructed of rolled sections, of forged steel, or of cast steel.

Typical non-equalized trucks (which are representative of British railway practice and are in service on a number of electric railways) are

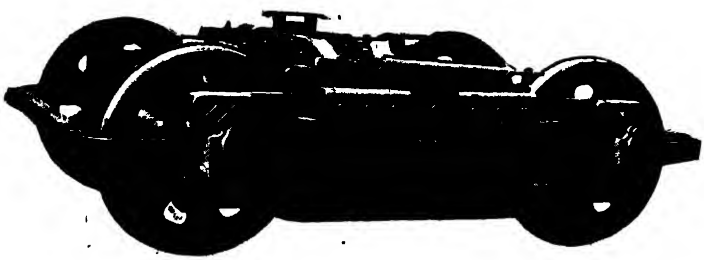


FIG. 278. Brill "27 M.C.B." Equalized Motor-truck.

illustrated in Figs. 277, 279, 280.* The trucks are built of pressed steel sections, which are riveted together. The side frames (or sole bars) *A* (Fig. 280) and the end frames (or head stocks) *B* are of channel section. The ends of the head stocks and the transoms (*C*) are flanged and riveted to the side frames, and each corner is reinforced by a gusset plate *D* in order to increase the rigidity of frame. The yokes for the axle boxes are reinforced by "U" pieces riveted to the back of the side frames, while the cast-steel horn blocks (or axle box guides) *E* are bolted to the front of the yokes. The truck frame is supported on the axle boxes by means of the lugs *F*. These lugs rest on short volute† springs *G*, which are carried on hangers *H* suspended from each end of the laminated semi-elliptic springs *J*.

The spring plank *K* (of channel section) is suspended from the transoms by swing links *L*, the upper ends of which are inclined towards the centre of the truck.‡ Each end of the spring plank is provided with two

* The author is indebted to the Leeds Forge Co. for the drawings from which Fig. 280 was made. This figure refers to a motor-truck for the London tube railways.

† In some cases spiral springs and concentric rubber springs are used.

‡ The swing links are arranged in this manner to counteract, to some extent, the centrifugal force acting on the coach when passing round curves. When the bolster swings outwards (on a curve) the inclined position of the links causes the outer portion of the coach to be raised and the inner portion to be lowered.

projections *M* which act as guides for the spiral springs supporting the bolster, similar projections being fitted to the under-side of the latter. The bolster *N* is of box section, and supports the car body on the centre bearing *O**, the upper portion of which is fixed to the underframe, while the two portions are maintained concentric by the king pin *P*. The

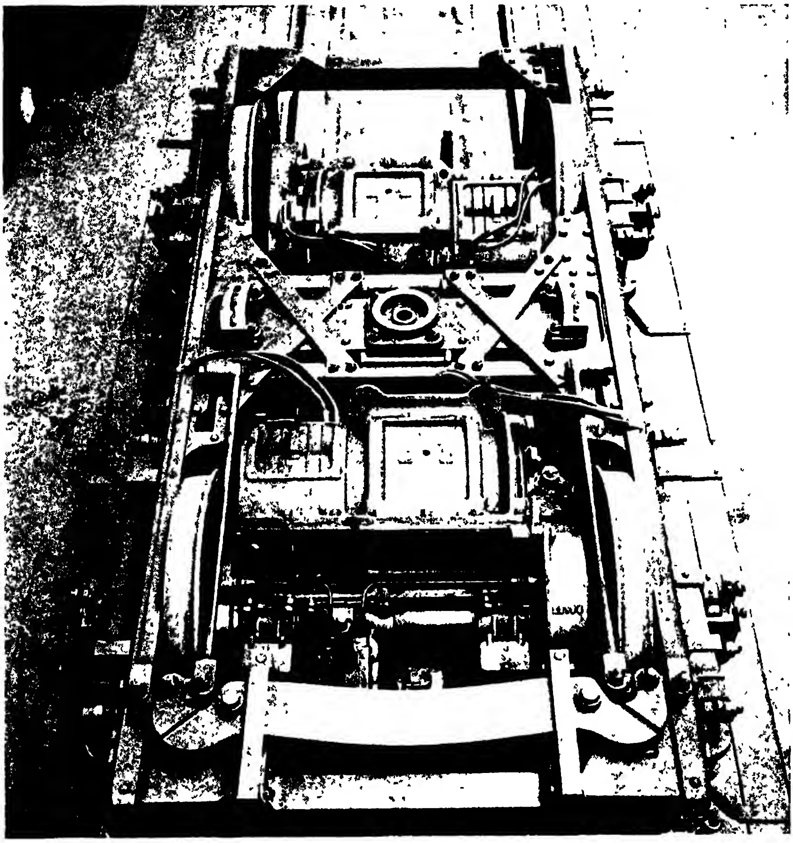


FIG. 279.—Top View of Motor-truck showing motors, brake-rigging, bolster, gussets and cross bracing.

(NOTE.—This illustration refers to a motor truck which was formerly in service on the single-phase lines of the L.B. and S.C. Railway.)

bolster is also fitted with side bearings *Q*, which engage rubbing plates on the under frame†. The swing of the bolster is limited by the ends of the bolster engaging plates *R* fixed to the side frames. The centre

* With trucks for tube railways the centre-bearing is of the ball-bearing type, as shown in Fig. 280; but with trucks for surface railways the centre-bearing is of the spherical-seated type.

† With coaches for surface railways the usual clearance between the side-bearings and the rubbing plates is about $\frac{1}{8}$ to $\frac{1}{16}$ in. with the body of the coach central. In cases where side oscillation of the coaches cannot be tolerated (as on tube railways) the body is carried on the centre-bearing and both side-bearings, which are of the roller (or ball) type to facilitate radiation of the track.

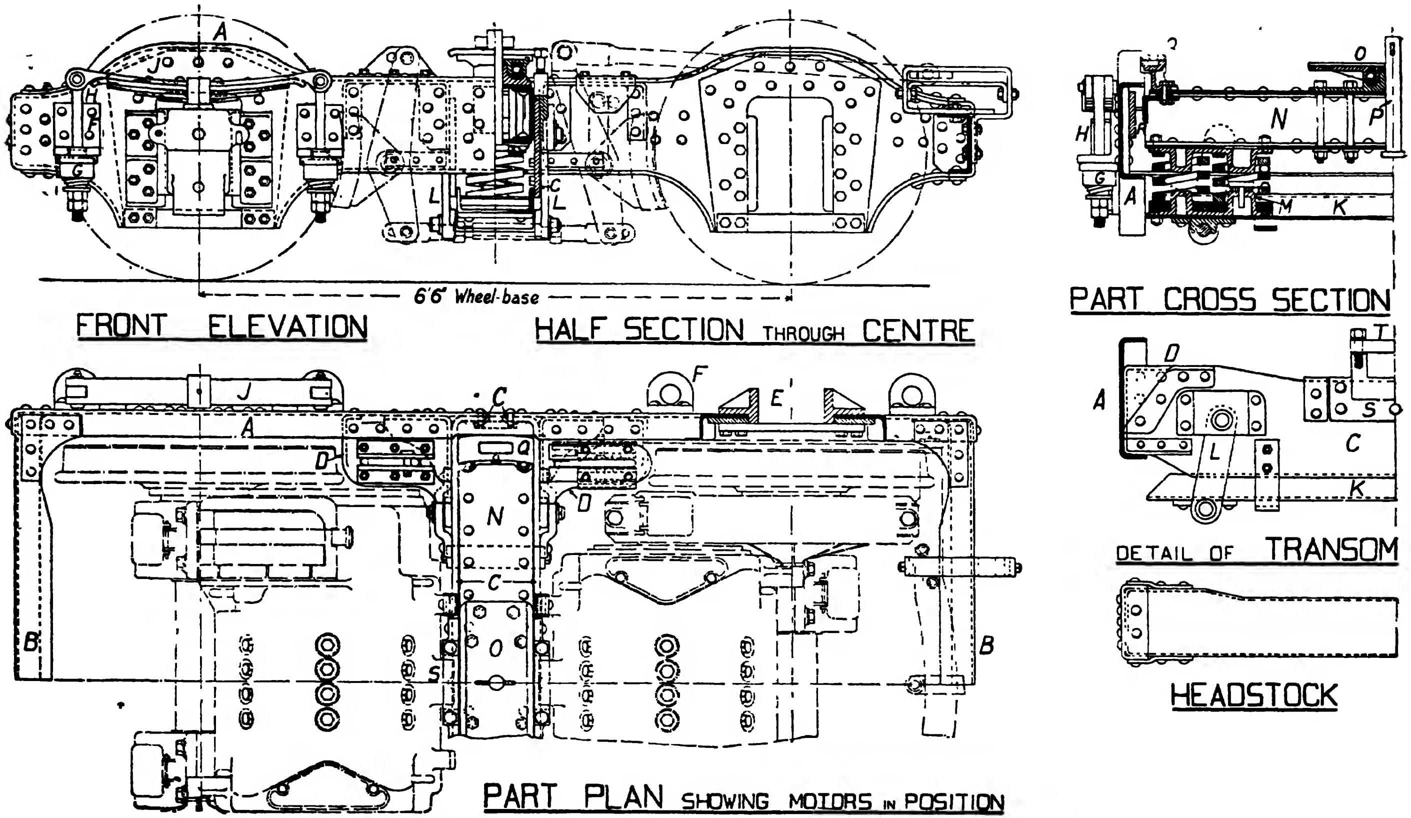


Fig. 280.—Fox's Pressed-steel Motor-truck. Built by the Leeds Forge Co. for the Centre-entrance Motor-cars on the London Electric (Tube) Railways.

and side bearings can be clearly seen in the view of the truck shown in Fig. 279.

The nose on the motor frame rests on a bracket *S* fixed to the transom, and is prevented from rising by the strap *T*.

Wheels and axles. The standard wheel diameter for rolling stock on steam railways in this country is approximately 43 in., and wheels of this diameter have been adopted on most of the suburban electrifications in this country, as the trailer coaches of the electric stock can be coupled to standard steam stock. With underground and other railways having a restricted loading gauge, wheels of smaller diameter (36 to 38 in.) must be employed.

The diameter of the axle at the motor bearings varies from about 6 in. to 7½ in., according to the size of the motor, while the diameter at the journals varies from 4½ in. to 6 in., this dimension being influenced by the weight of the coach.

Brake Rigging

It is the general practice on steam railways to fit two brake shoes to each wheel for all passenger rolling stock. With motor-trucks having a wheel base of from 6 ft. to 7 ft. there is considerable difficulty in finding room for the operating gear, since the position of the motors prevents the use of brake beams for the inner set of brake shoes. Consequently many motor-trucks of this wheel base are only provided with one brake shoe to each wheel. When the wheel base of the truck is of the order of 8 ft. to 10 ft., however, it is generally possible to provide two brake shoes to each wheel.

The use of outside-hung brake shoes enables brake beams to be adopted with a convenient arrangement of levers, but these advantages result in a tilting of the truck* when the brakes are applied, the front end of the truck being depressed and the rear end raised. This tilting action is more pronounced in trucks of the equalized type, due to the short spring-base and the method of mounting the truck frame on equalizer bars. When trucks of this type (with outside-hung brake shoes) are braked to give a high retardation, the tilting action compresses the front springs (on the equalizer bars) and removes a portion of the load from the rear springs. Thus when the car comes to rest a reaction is produced which results in a sudden backward jerk of the car body.

Brake rigging for inside-hung brake shoes. Fig. 281 shows a typical arrangement. As brake beams cannot be employed, the brake levers must be pivoted to the brake shoes and the force must be transmitted in line with brake shoes. In the present case divided brake rods *C* (Fig. 281) are employed in order to clear the wheels, and are attached, at one end, to a radius beam *B*, and at the other end to the brake levers *D*. The latter are pivoted to the brake shoes, and the lower ends are connected to the brake levers on the outer wheels by the equalizing rods *E*.

The brake shoes of the inner wheels are suspended, by links *G*, from

* The tilting action with outside and inside brake shoes is discussed fully in a paper by Mr. R. A. Parke, on "Railroad Car Braking" (*Transactions of the American Institute of Electrical Engineers*, vol. 20, p. 235).

brackets fixed to the side frames of the truck. The links G also support the weight of the brake levers D and a portion of the weight of the brake rods and equalizing rods.

The brake levers D' (for the outer wheels) are pivoted to their respective shoes, and the upper end of each lever is provided with a fulcrum F, formed by angle brackets fixed to the side frames. This fulcrum is adjustable in order to allow for the wear of the brake shoes, and the effective length of the equalizing rods is adjustable for the same reason.

The radius beam B is usually supported by guides L attached to the inner head stock (see Fig. 280), and the transverse movement of the

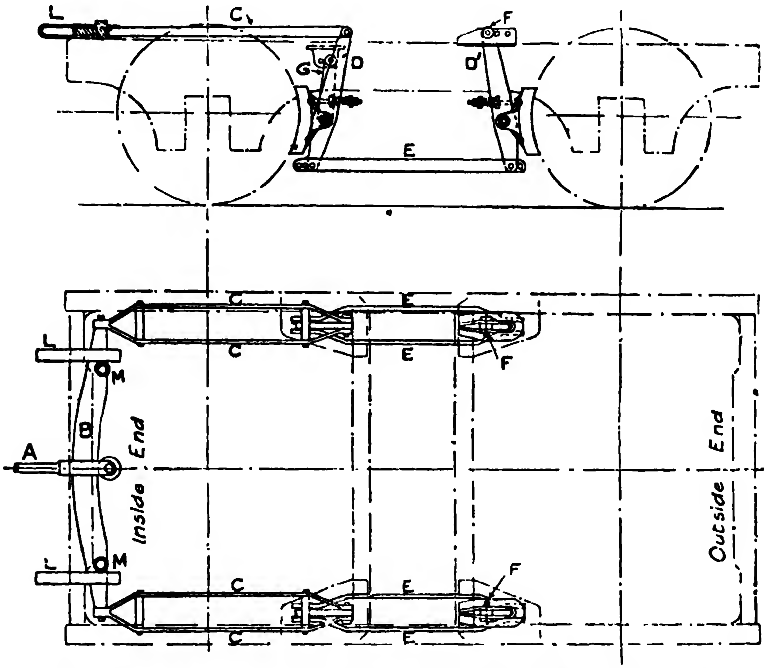


FIG. 281.—Diagram of Brake-rigging for Inside-hung Brake Shoes.

beam is limited by the rollers M engaging with these guides. The radius beam and guides can also be seen in Fig. 279.

When a tension is applied to the pull rod A, the brake shoes of the inner wheels come into operation first, and the thrust is then transmitted through the equalizing rods to the brake shoes on the outer wheels.

Brake rigging for two brake shoes per wheel. Fig. 282 shows the arrangement for a motor-truck. The outside brake shoes for both wheels are pivoted to the brake levers D, which are suspended from brackets H on the head stocks of the trucks. The brake levers D_1 of the inside shoes of the outer wheels are suspended in a similar manner from brackets F, fixed to the transom, but for the inner wheels of the trucks the inside brake shoes (and the brake levers D_2 connected to them) are suspended, from brackets G fixed to the opposite transom, by the links K. The inside brake levers D_1, D_2 are of a special " L " shape, and their lower

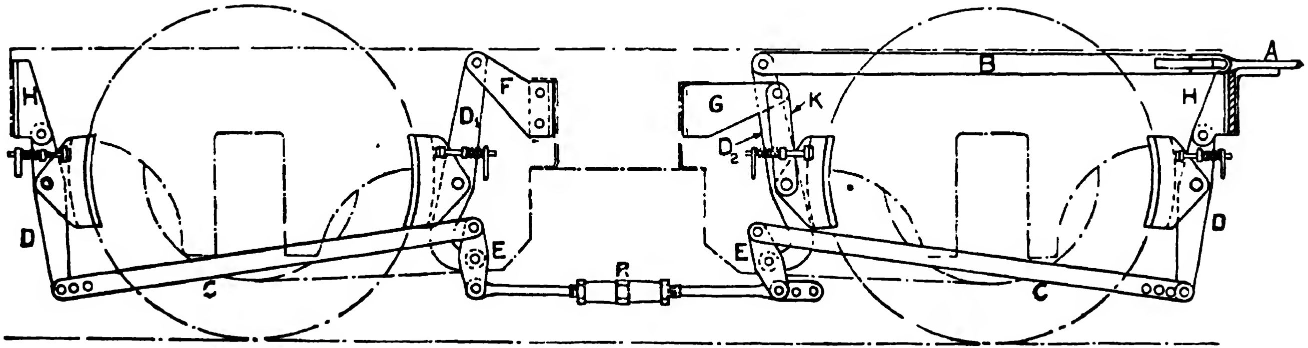


FIG. 282.—Diagram of Brake-rigging for Two Brake Shoes (without Brake-beams) to each Wheel.

ends are connected to the lower ends of the outside brake levers *D* through the equalizing levers *E* and the brake rods *C*, the other (lower) ends of the equalizing levers being connected together by the adjustable rod *R*. The upper ends of the inside brake levers D_2 (for the inner wheels of the truck) are connected to a radius beam *B* by divided brake rods, and the radius beam is operated by the pull rod *A* as explained above.

When the brakes are applied the inside shoes of the inner wheels come into operation first, and provide the brake levers D_2 with fulcrums. The thrust is then transmitted to the other brake shoes by means of the equalizing levers and brake rods.

EXAMPLES OF MOTOR-COACHES*

General. The general design of motor-coaches operating on the electrified lines of the larger steam railways in this country is, in many cases, similar to that of the standard rolling stock in use on those railways. In some cases the steam trailer stock has been reconstructed as motor-coach electric stock. In this reconstructed stock the control and auxiliary apparatus is located in the motorman's compartment (which adjoins the luggage compartment), so that the reconstruction of the underframe of the coach has been avoided. The existing underframe has had to be strengthened at some places, and new trucks have had to be provided.

When entirely new rolling stock is provided the control and auxiliary apparatus may be located either under the coach body or in the driving compartment. The former location is usually adopted with saloon-type coaches and low-voltage equipments, as for a given length of train the maximum passenger accommodation is obtained (which is an important consideration with urban railways on which the traffic is dense and the station platforms are of limited length). The compartment arrangement of the control apparatus is usually adopted for suburban railways which have compartment type stock with luggage compartments, as the location of the control apparatus above the floor level gives greater accessibility and facilitates inspection and adjustments. This arrangement is also desirable with high-voltage equipments, but it is not adopted universally.

Examples of 1500-volt control equipment arranged for underframe mounting are shown in Fig. 168. In some cases, with high-voltage direct-current equipments, the compressor motor, motor generator, and rheostats are located in the same compartment as the control apparatus, but in other cases the auxiliary apparatus is mounted under the coach body. In all cases where a "high-tension" compartment is provided the doors of this compartment should be interlocked with the overhead current collector, so that the doors cannot be opened unless the collector has been previously lowered. As an additional safeguard an isolating switch (which is connected between the leading-in wire and the main circuit breaker) is interlocked with the doors.

Motor-coaches for low-voltage, direct-current railways. A **District Railway** (London Underground Railways) steel motor-coach is shown in Fig. 283. The coach is of the saloon type, with centre and end sliding

* Dimensions and data are given in Table XI, p. 412.

Fig —S ·h o ·ilway, London.

FIG. 284.—Centre-entrance Motor-car of the London Electric (Tube) Railways.

doors. The underframe is of the trussed type, and is mounted on bogie trucks, of which one is equipped with motors. The control and auxiliary apparatus is fixed to the underframe, and the boxes containing the contactors, reverser, and circuit-breaker can be seen in the illustration. Each truck is equipped with positive and negative collector shoes, and all collector shoes of like polarity are connected in parallel by means of " bus-line " cables.

A typical motor-car in service on the **London Electric (Tube) Railways** is shown in Fig. 284. The car is of the saloon type and is constructed principally of steel (see Figs. 275, 276), any essential woodwork being rendered non-inflammable. It is mounted on bogie trucks, of which one is equipped with motors.*

The control and auxiliary apparatus is located in a steel compartment above the motors, the floor of this compartment being about 20 in. higher than that of the passenger compartment in order to clear the motors. Removable louvred shutters are provided for the purposes of ventilation and inspection of the apparatus.

Fig. 285 shows a portion of the apparatus in the control compartment of one of the latest motor-cars, the remainder of the apparatus being located on the opposite side of the (central) gangway. These equipments are arranged for automatic acceleration. Provision is made for cutting out a defective motor and for operating the car on the remaining motor. The accelerating relay and the switches for the control and auxiliary circuits are mounted on the steel partition which divides the control and driving compartments.† Views of a driving compartment are shown in Fig. 286.

The passenger compartment is entered either at the centre (the doors of this entrance being operated pneumatically) or at the trailer end from a platform. The adjoining car has a similar platform, and each is provided with collapsible gates, which, together with the end doors of the saloons, are operated manually by a conductor. The platforms facilitate the distribution of passengers between adjacent cars, and the conductor superintends the entraining and detraining of the passengers, giving a bell signal to the guard immediately this is completed. In this manner heavy passenger traffic is handled very expeditiously, and the duration of stop rarely exceeds 20 seconds.‡

Trains normally consist of two motor-cars and four trailers, the motor-cars being at the ends. For light traffic the trains are divided, and consist of one motor-car and two trailers.

The **Southern Railway's** motor-coaches have the control and auxiliary apparatus located in a separate compartment at the driving end of the coach. This compartment adjoins the luggage compartment, and the arrangement of the apparatus is shown in Fig. 287. Only one truck (viz.

* On tube railways the Ministry of Transport will allow motors to be carried only at one end of a motor-car, and no main cables may be carried through the train. Moreover, the whole of the control and auxiliary apparatus for each motor-car must be located in a steel compartment above the motors.

† In earlier motor-cars these switches and the accelerating relay were mounted on a slate panel in the driving compartment. The present arrangement, however, occupies less space and results in easier installation and wiring.

‡ Further information on the traffic organization of the London Underground, and other British Railways, is given in *British Railway Practice*, by Bernard E. Holt.

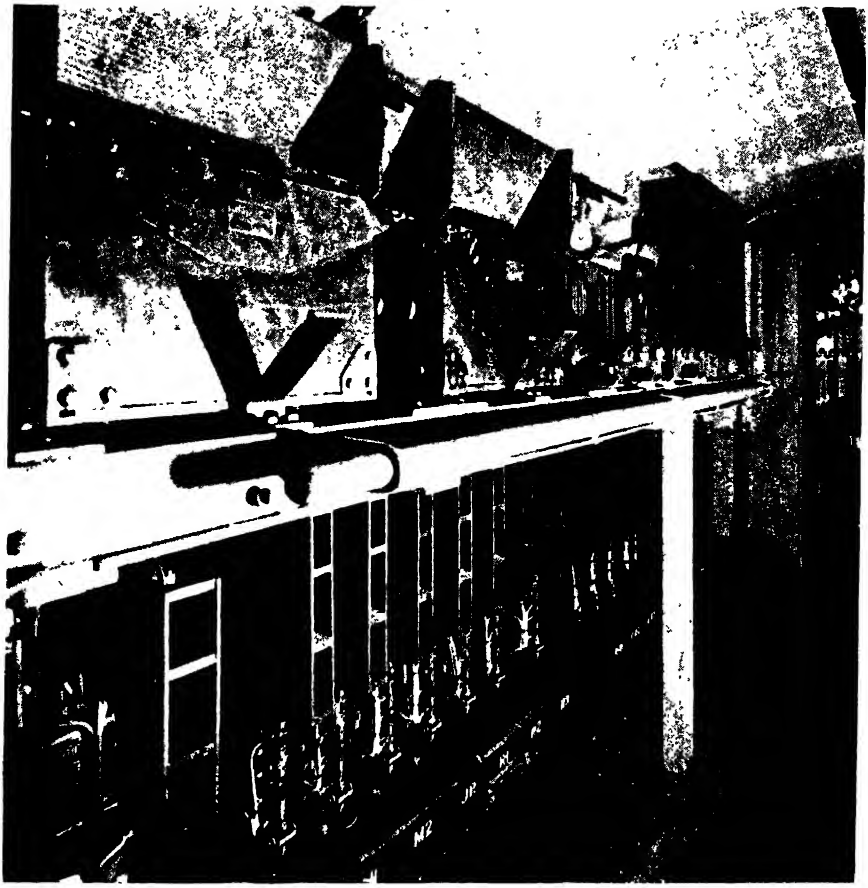


FIG. 285.—View of Control Compartment of Motor-car. (General Electric Equipment).

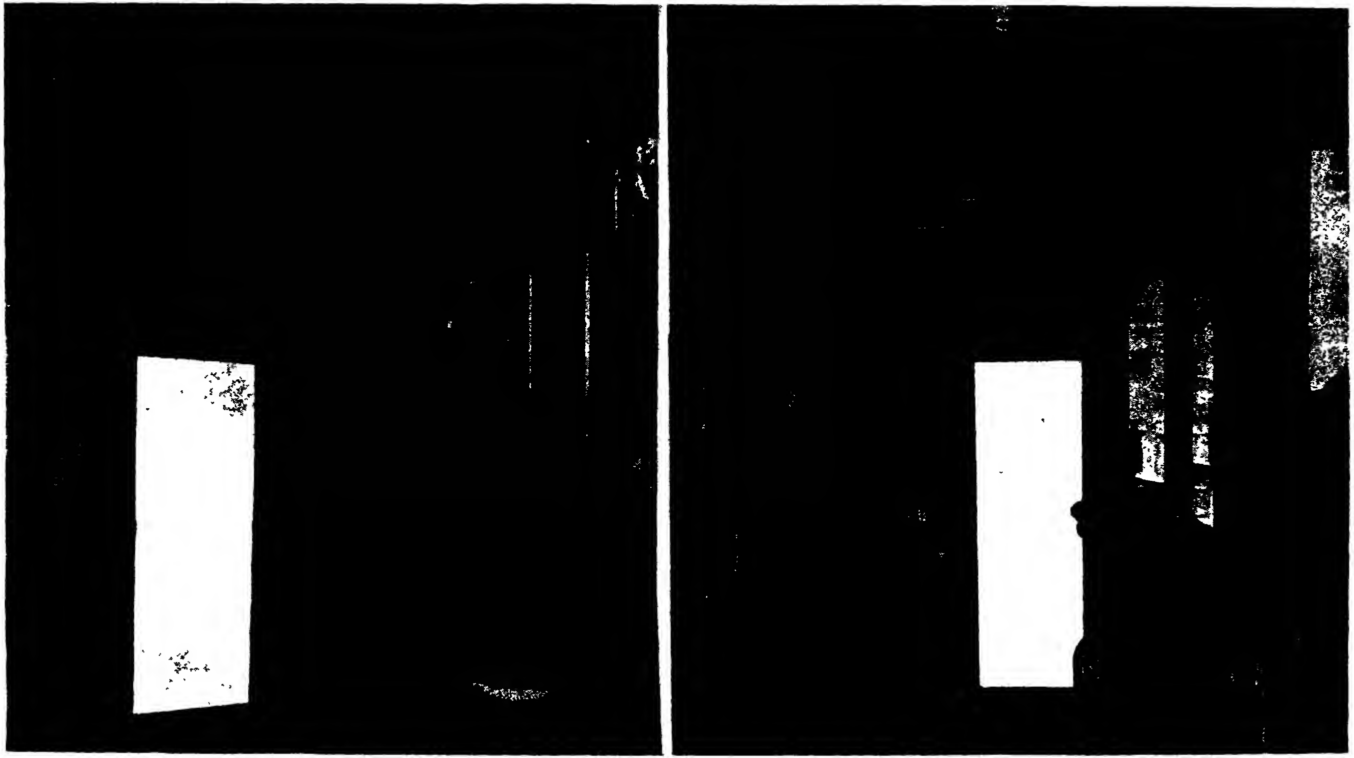


Fig. 286.—Views of Driving Compartment of Motor-car in Service on London Electric (Tube) Railways. (General Electric Equipment.)

that below the control compartment) of each motor-coach is equipped with motors, but these are of relatively large output (300 h.p.).

The rolling stock on this railway is of the compartment type and follows the general design of the steam rolling stock; in fact, a large

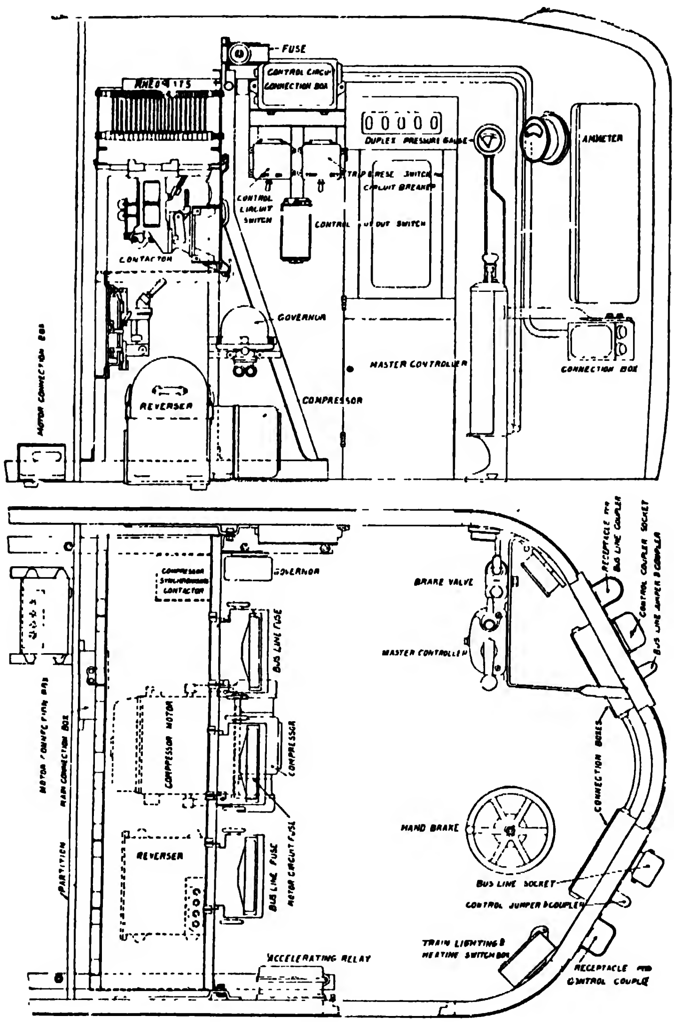


FIG. 287.—Elevation and Plan of the Control and Driving Compartment of a Motor-coach on the Southern Railway (Western Section).

portion of the suburban steam rolling stock was reconstructed for electric service. Two motor-coaches are permanently close-coupled to a trailer coach and form a "train unit," the trains being made up of one, two, or more units as required. As the trailer coach of each unit is arranged

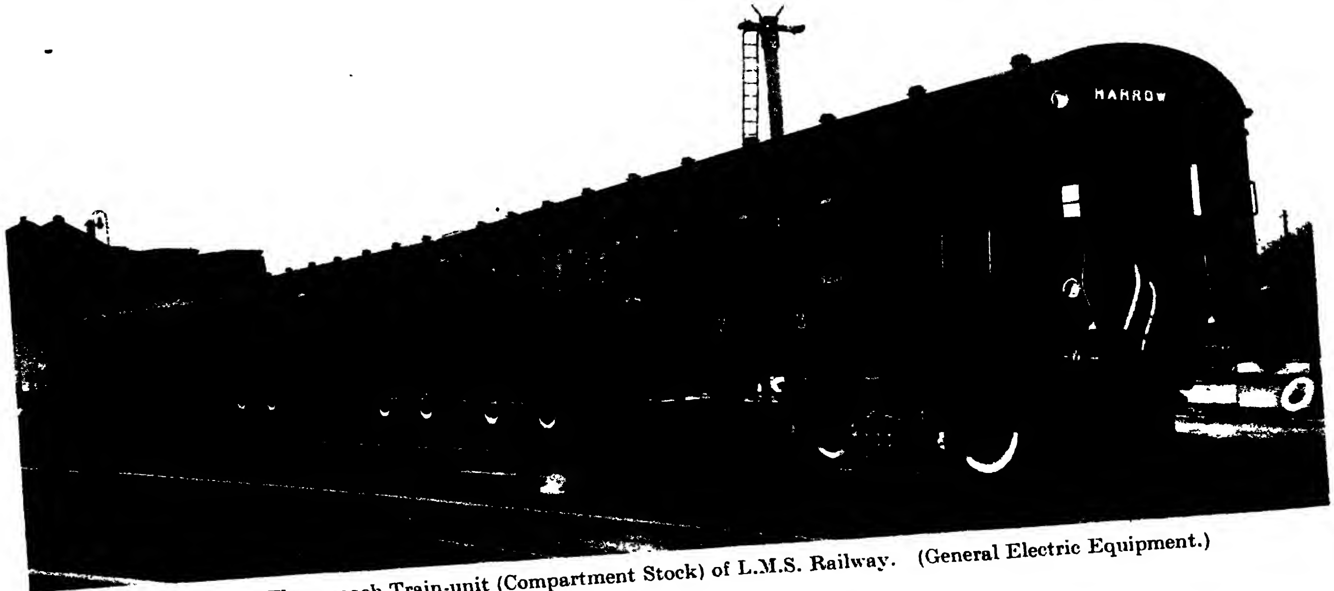


FIG. 288.—Three-coach Train-unit (Compartment Stock) of L.M.S. Railway. (General Electric Equipment.)

between the motor-coaches of that unit, no driving compartments are provided in any of the trailer coaches.

The original motor-coaches had the reconstructed (driving) end of parabolic shape (see Fig. 287) to reduce the head resistance (see Chapter XVIII), but the later motor-coaches have almost flat ends.

Fig. 288 shows a three-coach train unit of the **London, Midland and Scottish Railway** (London suburban lines) which is representative of British compartment-type rolling stock. In this case the train unit consists of one motor-coach and two trailers, one of the latter having a driving compartment and current-collecting gear. The motor-coach has

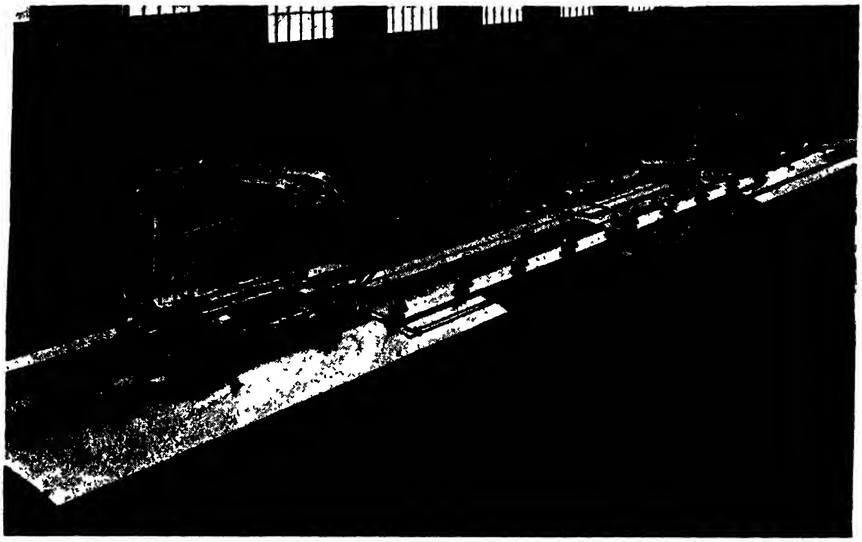


Fig. 289.—1500-volt Motor-coach, Cape Town Suburban Railways. (English Electric Equipment.)

a four-motor equipment, and the whole of the control apparatus is located in a compartment at the driving end.

Motor-coaches for high-voltage, direct-current railways. These railways are usually supplied from an overhead distribution system, and the current collectors are of the pantagraph type. The **Manchester-Bury** (1200-volt) section of the L.M.S. Railway, however, is an exception; side-contact collector rails being employed for distribution, and collector shoes (p. 336) for current collection.

The motor-coaches on this line are of the end-door saloon type (with communicating doors between the coaches) and are constructed mainly of steel. Each coach is equipped with four 200 h.p., 1200-volt, motors; a 10 kW., 1200/100-volt, rotary transformer (which supplies the control, auxiliary, and train lighting circuits); a 5 h.p., 100-volt motor coupled to an exhauster for the vacuum brake. The rotary transformer, exhauster set, and starting rheostats are located under the coach. The control

equipment* is located in two high-tension compartments (one at each end of the coach), each of which contains the control gear and isolating switches for a pair of motors. An auxiliary compartment contains the control gear and isolating switch for the rotary transformer. The isolating

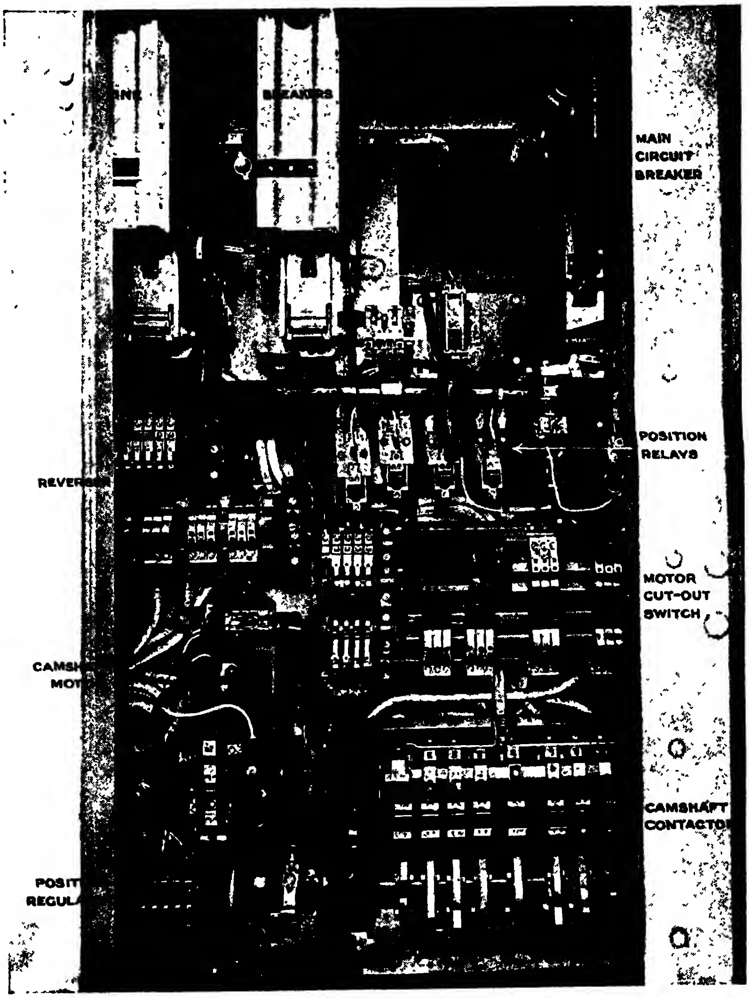


FIG. 290. High-tension (Control) Compartment of Motor-coach. (English-Electric Equipment.)

switches are interlocked with the doors of the compartments and prevent the latter being opened when the former are closed. The driving compartments are adjacent to the high-tension compartments.

The **Cape Town Suburban Railways** provide an example of 1500-volt

* A full description of the control equipment and motors is given in *Electric Motors and Control Systems*, pp. 253–259.

motor-coach equipment with pantagraph current collectors. Each motor-coach has two vacuum-controlled pantagraphs, either of which can be used as desired, the selection being by a selector cock in the driving compartment of each coach. The raising and lowering of the pantagraphs throughout the train is controlled by electrically-operated valves on the several coaches, the operating current being taken from the control circuit through a master switch in each driving compartment. The two pantagraphs on each coach are inter-connected by a bus line on the roof of the coach (Fig. 289), from which a connection is taken through a choke coil (with a tap to a lightning arrester) and fuse to the high-tension compartment. The pantagraphs on the separate coaches, however, are not inter-connected (i.e. each motor-coach is a separate unit in so far as its high-tension side is concerned).

The control gear for the motor equipment (viz. four 200 h.p., 750-volt motors) is contained in a main compartment (Fig. 290); that for the auxiliary machines, together with the isolating switches, is contained

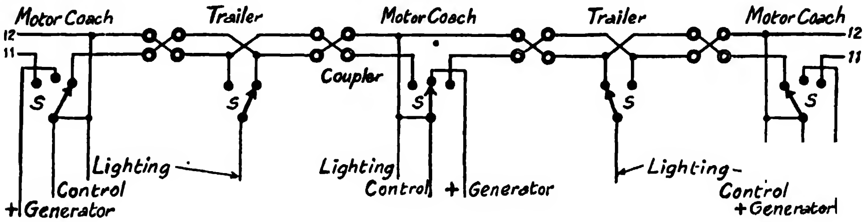


FIG. 291.— Arrangement of Twin Bus-line for Control and Lighting Circuits.

in an adjoining compartment, the door of which is interlocked with the isolating switches and also with the pantagraph.

The auxiliary equipment is mounted on the underframe and consists of a 5·5 kW., 1500/110-volt, motor generator (which supplies the control and lighting circuits), and a rotary exhauster coupled to a 1500-volt motor. The exhauster runs continuously and maintains a vacuum of 20 in. of mercury in the train pipe, except during brake applications, when it is cut off by an electrically-operated valve. On the release of the brakes the exhauster is speeded up by weakening the field of the motor, a special contactor (which is operated by a contact on the brake valve) being provided for this purpose.

A feature of interest is the provision of a low-voltage twin bus line, together with selector switches, for the control and lighting supply on each coach. The arrangement is shown diagrammatically in Fig. 291. Three-way and two-way selector switches are provided in each motor-coach and trailer respectively, and, according to their positions, (1) the leading motor-coach may receive its lighting and control circuit supply either from its own motor generator or from a motor generator on one of the coaches coupled to it; (2) the lighting circuits of any other motor-coach on the train may be supplied from either the motor generator on that coach or from a motor generator on a coach in front or behind; (3) the lighting circuits of any trailer coach may be supplied from the motor-coach either in front of or behind it.

Fig. 292 shows an alternative arrangement of a high-tension compartment with all-electric, cam-shaft, control gear. In this case the whole of the auxiliary apparatus and starting rheostats are located in the high-tension compartment, the rheostats being mounted near the roof. This arrangement of the control and auxiliary apparatus in a single compartment is generally preferred to the distribution of the apparatus

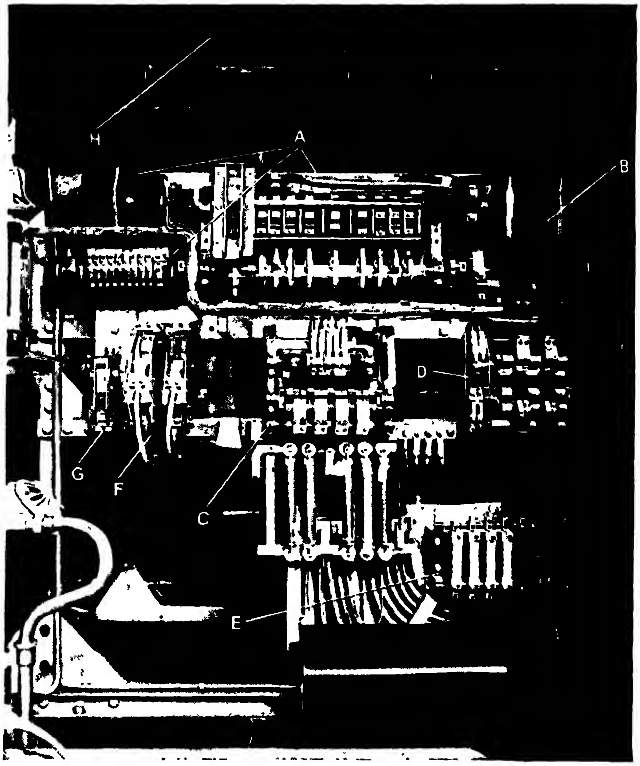


FIG. 292.—High-tension (Control) Compartment of Motor-coach with English-Electric Equipment.

A, cam-shaft controller; *B*, line contactors; *C*, reverser; *D*, motor cut-out switch; *E*, control circuit rheostats; *F*, field shunting contactors; *G*, cam-shaft motor relay; *H*, starting rheostats.

under the coach, as it conduces to greater safety and protects the auxiliary apparatus from road dust.

A motor-coach (equipped for a 2400-volt supply circuit) for interurban service in Central Italy is shown in Fig. 293. This coach has accommodation for 55 seated passengers, its weight, unloaded, being 29 tons. It is normally operated in conjunction with two trailer coaches and one or two goods' wagons, the total train weight, loaded, being about 90 tons. The electrical equipment comprises four 100 h.p., 1200-volt, 6-pole, self-ventilated motors; a cam-operated main controller with pneumatically-operated reversing drums; a pneumatically-operated main switch; and an air compressor. The controller, reversers, and main switch are located in a high-tension compartment in the centre of the coach; the cam-shaft of

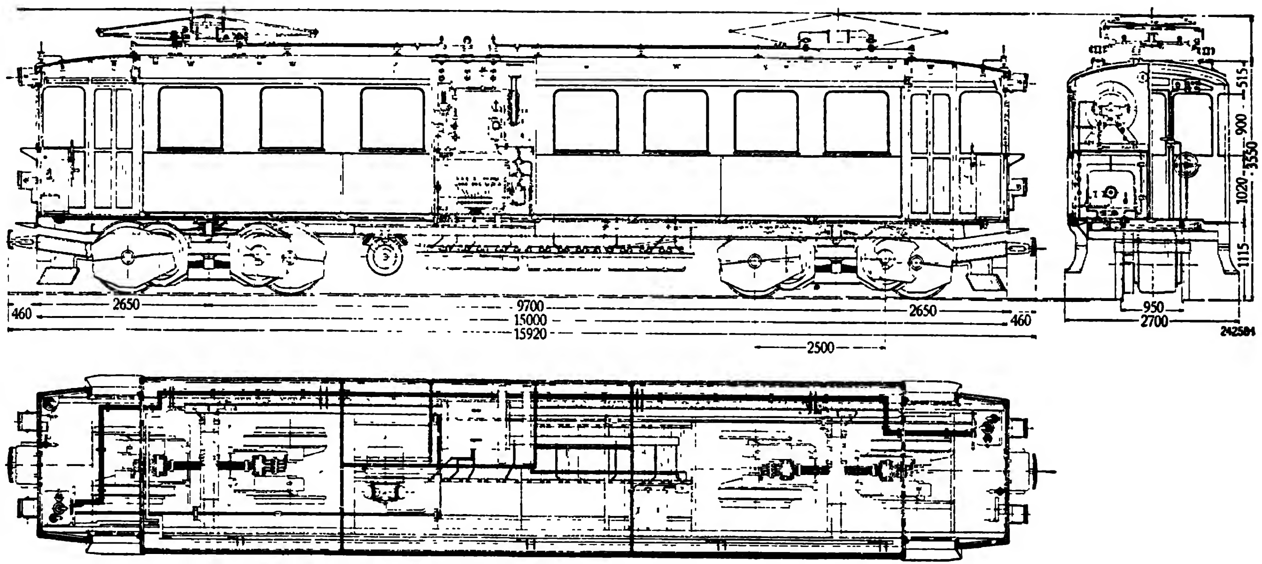


FIG. 293.—Arrangement of 2400-volt Direct-current Motor-coach for Interurban Railway. (Brown-Boveri.)

the controller being operated through shafts and bevel gearing from hand-wheels in the driving cabs. The compressor and rheostats are supported from the underframe of the coach; the latter being enclosed in a sheet steel casing fitted with inspection covers and ventilating openings.

The heating of the motor-coach and also that of the trailers is supplied

FIG. 294.—High-tension (left) and Low-tension (right) Compartments on Single-phase Motor-coach.

directly from the traction circuit, the connection between the coaches being mounted on the roof. The lighting circuits are supplied, at 12 volts, from accumulators.

Motor-coaches for single-phase railways. The motor-coaches which were formerly in service on the suburban lines of the **London, Brighton and South Coast Railway** provide a good example of the arrangement of

the control and auxiliary apparatus. In this case the main transformer, contactors, and compressor are mounted on the underframe ; the high-tension apparatus is located in a steel compartment ; and the low-tension protective apparatus is located in an adjoining compartment. Fig. 294 is a view of the high- and low-tension compartments, which adjoin the driving and luggage compartments. The upper part of the high-tension compartment contains the fuses for the main and auxiliary transformers, choke coil, earthing switch, and lightning arrester. The central part of the compartment contains the electrically-operated oil switch for the main transformer, and the current transformer for supplying the overload relay and the ammeter in the driving compartment. The auxiliary transformer (which supplies the control and lighting circuits)* is bolted to the floor. The door of this compartment is mechanically interlocked (by the levers shown in the roof) with the bow collectors, and cannot be

FIG. 295.—Single-phase Motor-coach, German State Railways. (Siemens-Schuckert Equipment.)

opened if either bow is raised. Moreover, the opening of the door closes the earthing switch, and so earths all the high-tension wiring.

The low-tension compartment contains the control circuit cut-out switches, fuses, and connection boxes.

In a number of Continental motor-coaches in which the contactor system of tap-changing is employed, the contactors and other low-voltage apparatus are mounted on the underframe, and the high-tension apparatus, including the transformer, is located in a central compartment in the coach body. Such an arrangement is standardized on the **German State Railways,** a typical motor-coach being shown in Fig. 295. A contactor group for this coach is illustrated in Fig. 192.

Fig. 296 illustrates a motor-coach (Swiss Federal Railways) for coupling to passenger (trailer) coaches. No passenger accommodation is provided on the motor coach, the interior of which is utilized for luggage and parcels.

Detail views of one of the trucks and the mounting of a motor are shown in Fig. 297, in which the flexible gear-wheel should be noted. Detail views of the motor are shown in Fig. 60, page 110. The control equipment is of the electro-pneumatic individual contactor type, and is arranged for automatic acceleration and regenerative braking. The contactors and

* A simplified diagram of connections is given in *Electric Motors and Control Systems,* p. 318.

Fig. 296.—Single-phase Motor-coach, Swiss Federal Railways. (Oerlikon.)

reversers, together with the high-tension switchgear, are contained in steel compartments in the interior of the coach, the contactor and reverser compartment being shown in Fig. 298. Another compartment contains the motor-driven blowers and oil pump for cooling the transformer and traction motors, together with the 36-volt, direct-current, train-lighting generator (which is coupled to one of the blower sets).

The main transformer is mounted under the coach, and is cooled by

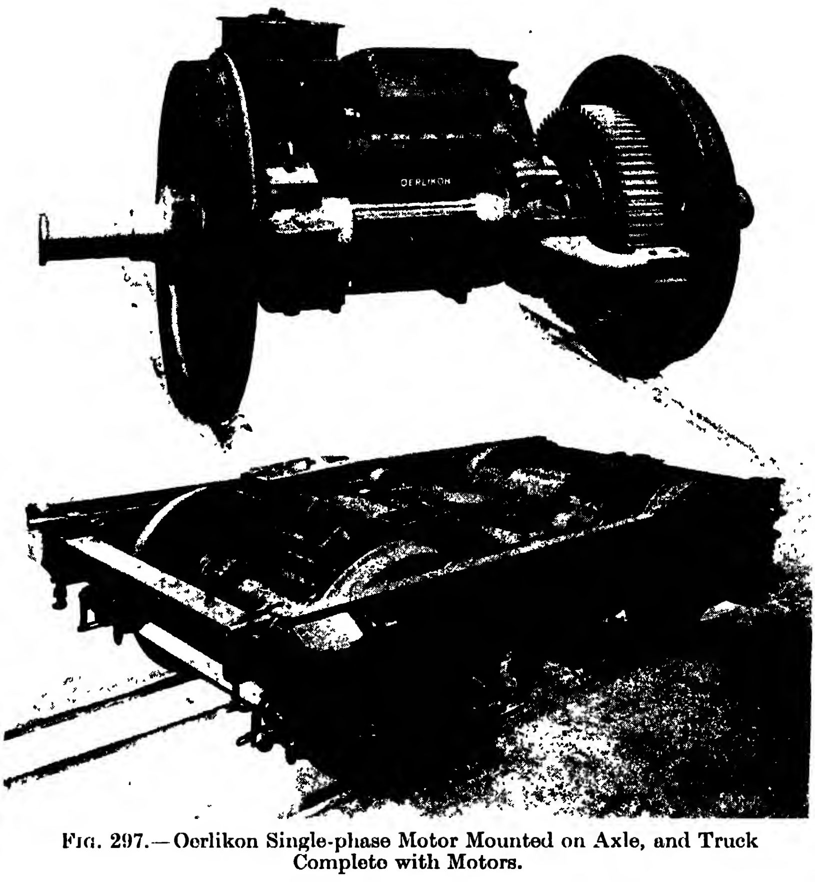


Fig. 297.—Oerlikon Single-phase Motor Mounted on Axle, and Truck Complete with Motors.

forced circulation of the oil. The oil is cooled in an external tubular cooler by an air blast.

The motor-driven air-compressor and the battery of accumulators (for train lighting) are also carried from the underframe.

A departure from the usual design of motor-coach is due to the Oerlikon Co., and consists of the use of a single frame-mounted motor, of moderately large size, mounted upon a locomotive truck to form a self-contained driving unit (or locomotive) which is close-coupled to the

passenger compartment. Fig. 299 shows the arrangement. The motor has a rating of about 500 h.p., and is mounted on the frame of a three-axle locomotive truck having two coupled driving axles and a pony axle. It is geared to a transverse shaft which is fitted with cranks, to which the crank pins on the driving wheels are coupled by an inverted "scotch yoke" (p. 432). The truck frame is close-coupled to the underframe of the passenger compartment, which is mounted upon a bogie truck at

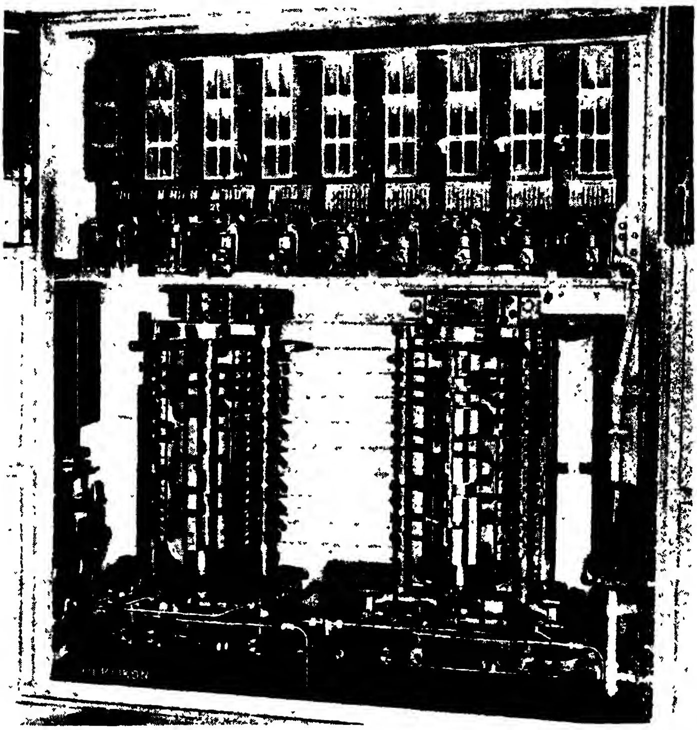


FIG. 298.—Oerlikon Electro-pneumatic Contactors and Reversers in Control Apparatus Compartment of Motor-coach

the far end and a single axle at the near end. The whole of the electrical equipment is contained in a body built upon the locomotive truck.

BRAKES

The brakes on railway passenger rolling stock are always operated by power, since it would be impossible to obtain sufficient braking force with hand-operated brakes. Hand brakes, however, are fitted to motor-coaches and guards' compartments for operation by the motorman or guard in cases of emergency.

Two **types of power brakes** have been developed, viz. the compressed air (or Westinghouse) brake, and the vacuum brake. The former brake is largely used on electric railways, and is also extensively adopted in America on steam railways. The vacuum brake is standard on all our

TABLE XI

Data of Motor-coaches—British Railways—4′ 8½″ Gauge—Direct-current Equipments

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Type of coach	Saloon	Saloon	Compartment	Saloon	Compartment	Saloon	Saloon	Compartment	Compartment	Saloon	Saloon	Compartment
Length of coach	60′ 5″	63′ 7¼″	59′ 0″	57′ 0″	59′ 0″	63′ 7″	52′ 10″	42′ 4½″	55′ 4¾″	50′ 2″	51′ 10¾″	64′ 2″
Width of coach	9′ 10¼″	9′ 10	9′ 0″	9′ 0″	9′ 0″	9′ 4″	8′ 9″	8′ 3″	8′ 9″	8′ 11½″	8′ 6¼″	8 0″
Seating accommodation	60	80	84	48	84	74	37	30	50	44	30	80
Distance between bogie centres	40′ 6″	45′ 0″	39′ 6″	37′ 6″	39′ 6″	45′ 0″	35′ 0″	25′ 0″	35′ 6″	34′ 0″	33′ 5½″	44′ 0″
Wheel-base*	8′ 0″	10′ 0″	8′ 9″	8′ 9″	8′ 9″	9′ 0″	7′ 9″	7′ 0″	8′ 0″	7′ 10″ 7′ 3″	6′ 6″ 5′ 7″	8′ 9″ 8′ 0″
Diameter of wheels* (in.)	43⅝	43⅝″	43⅝″	43⅝″	43⅝″	43⅝″	36″	38″	38″	36″ 30″	36″, 40″† 30″, 32″†	43″
Gear ratio	1·95	2·48	3·33	3·33	3·33	2·36	2·75	3·37	2·95	3·37	3·7, 4·18†	2·81
Number of motors per coach	4	4	4	4	4	4	4	4	4	2	2	2
Rated h.p. of each motor	150	250	240	260	280	200	200	200	275	240	240	275
Weight of bogie truck without motors* (tons)	4·85	8·85	7·45	7·45	7·45	7·12	6·1	4·6	7·55	5·93 5·62	6·1 3·44	8·5 5·6
Weight of motor with gear and gear case (tons)	2·92	4·12	3	3·4	3·7	3·48	2·7	2·8	2·65	2·72	2·72	3·125
Weight of truck with motors and brake gear (tons)	11·0	17·85	13·45	14·25	14·85	14·08	11·5	10	12·85	11·37	11·54	14·75
Weight of complete electrical equipment, not including auxiliary apparatus for brakes (tons)	14·68	23·67	17·7	20	21	21·8	18	16·2	14	6·52	6·52	10·35
Weight of car-body complete with all equipment (tons)	24	31·7	26·1	26·25	26·3	25·84	23·6	19	28·1	15·9	14·31	18·8
Weight of coach completely equipped (tons)	46	67	53	54·75	56	54	46·6	39	53·8	33·89	29·29	39·7
System of control	Direct	←——Multiple unit——→										

* Upper figures refer to motor truck, lower figures refer to trail truck. † Some motor-coaches have motor trucks with 36″ wheels, and others have 40″ wheels.

Reference: I, II, III. L.M.S. Ry. (Liverpool-Southport Section); IV, V, L.M.S. Ry. (Euston-Watford Section); VI, L.M.S. Ry. (Manchester-Bury (1200 v.) Section); VII, VIII, IX, Metropolitan Ry. (London); X, Metropolitan-District Ry. (London); XI, London Electric (tube) Rys.; XII, Southern Ry.

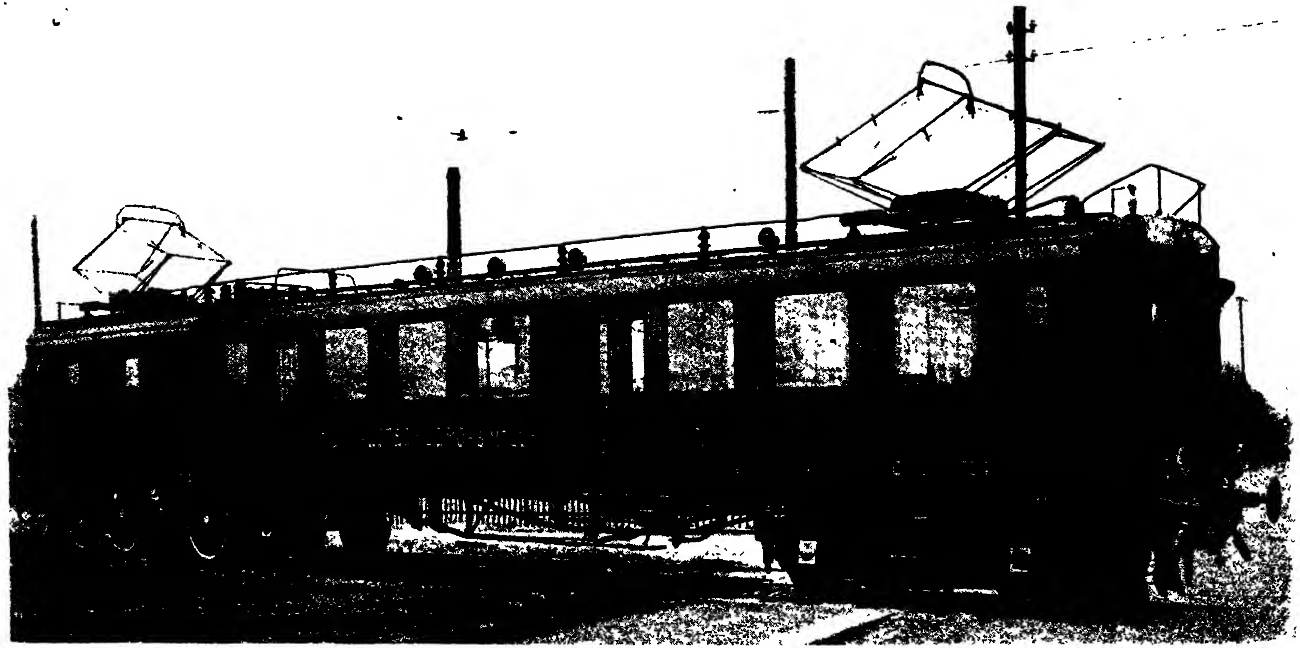


FIG. 299.—Oerlikon Motor-coach with Self-contained Driving Unit.

large steam railways, and has been adopted on some electrified lines (e.g. the Lancashire sections of the London, Midland and Scottish Railway, and other railways abroad).

For electric railways the compressed-air brake possesses some advantages over the vacuum brake, as compressed air can be stored so that a quick release of the brakes can be obtained; whereas, with the vacuum brake, the vacuum must be created by means of a pump or exhauster. This disadvantage, however, can be overcome by the use of either vacuum reservoirs and equalizing valves, or a two-speed exhauster.

The vacuum brake. In its simplest form this brake consists of a vertical cylinder (called the brake cylinder) fitted with a piston and piston rod, the latter operating the brake rigging through suitable levers. A vacuum is maintained continuously on the top of the piston, while air—at atmospheric pressure—can be admitted to, or exhausted from, the underside of the piston. Under normal conditions (i.e. brakes off) a vacuum is maintained on both sides of the piston, and the latter rests against the lower cylinder cover. When an application of the brakes is required, the vacuum is broken on the underside of the piston and the latter is forced upwards, thereby applying the brakes. The brakes are released either by re-creating the vacuum, or by equalizing the pressure on each side of the piston.

In practice each coach is equipped with one or two brake cylinders (according to the nature of the brake rigging on the bogies) which are connected to the "train pipe," as shown in Fig. 300. The latter is continuous throughout the train, and is connected to the operating (or driver's) valve on the locomotive or motor-coach. On steam trains this valve is a combination of an air valve and two steam ejectors, one large and one small. Under normal conditions the small ejector maintains the vacuum in the train pipe, while the large ejector is only operated for releasing the brakes. On electric trains these ejectors are replaced by a motor-driven exhauster (or vacuum pump) which is run at two speeds—one being double the other—the higher speed being only used for releasing the brakes. With continuous-current equipments the lower speed is obtained by inserting a rheostat in series with the motor, and the rheostat is cut out when the driver's valve is moved to the "off" or "release" position. With single-phase, alternating-current equipments two or more operating speeds for the exhauster motor can readily be obtained from tappings on the transformer.

One type of vertical **brake cylinder** (manufactured by the Vacuum Brake Co.) is shown in Fig. 300. The cylinder *A* is combined with the vacuum chamber *B*, which is provided with trunnions for mounting in a vertical position under the coach. The piston *C* is an easy fit in the cylinder, and is provided with a rolling rubber ring *D*, while the piston rod *E* is provided with a packing gland in the lower cylinder cover. The sides of the piston near the top are provided with three small holes and ball valves (one of which is shown at *F*), by means of which communication can be established between the vacuum chamber and the underside of the piston when the pressure in the former exceeds that in the lower portion of the cylinder. This portion of the cylinder may be connected directly to the train pipe, or the connection may be made through an

automatic valve as described below. The vacuum chamber can also be connected to the train pipe through the release valve *G*, which is normally held on its seat by atmospheric pressure acting on a diaphragm.

When the brake is "off" the vacuum is maintained in the train pipe, vacuum chamber, and on the underside of the piston, and any air which finds its way into the vacuum cylinder is exhausted through the ball valves. When an application of the brakes is required, the train pipe is opened to the atmosphere, and air is admitted to the underside of the piston, which is moved upwards. The force with which the brake shoes are applied to the wheels depends on the rapidity with which the vacuum

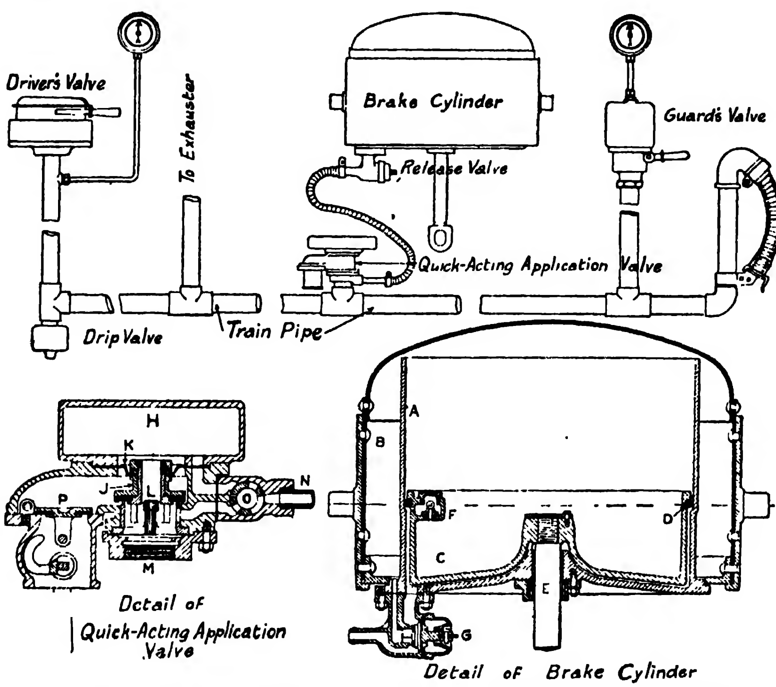


FIG. 300.—General Arrangement of Essential Parts of Vacuum Brake (Vacuum Brake Co.).

is destroyed, while the brakes may be partially released by partially restoring the vacuum.

The air in the train pipe is prevented from reaching the vacuum chamber (and the top of the piston) by the ball valves and the packing ring. The function of the release valve is to allow the brakes to be released on a coach which is disconnected from the locomotive. This is done by lifting the valve from its seat, which equalizes the pressure on both sides of the piston, thereby allowing the latter to return to the bottom of the cylinder.

When a quick-acting brake is required on a long train, the brake cylinders are not connected directly to the train pipe but to auxiliary valves which are connected to the train pipe and to the atmosphere. A cross-section of one type of auxiliary valve (called a "quick-acting

application valve ") is shown in Fig. 300. A rubber-seated valve J is provided with a diaphragm K, over which is placed a small air chamber H. This air chamber communicates with the train pipe through a small annular space formed by the fixed stem L and a central hole in the body of the valve J. The underside of the diaphragm and the top of the valve J can be placed in communication with the atmosphere by means of the hinged clap valve P. Under normal conditions valve J is maintained on its seat by the excess of pressure on the upper part of the valve, the underside of the latter and the top of the diaphragm being connected

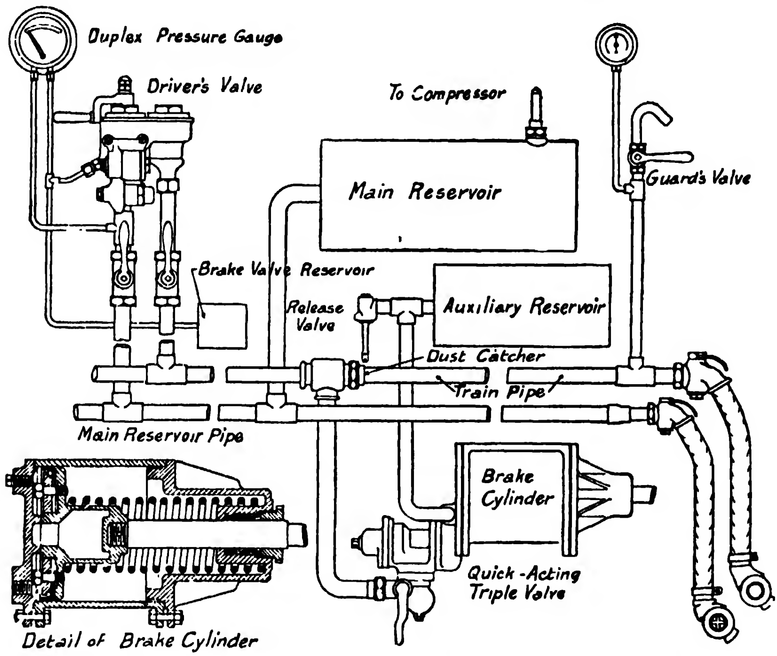


FIG. 301.—General arrangement of essential parts of Westinghouse Quick-acting Compressed-air Brake (Westinghouse Brake Co.).

to the train pipe (at M). When an application of the brake is required, the vacuum in the train pipe is destroyed by operating the driver's valve. This unseats the valves J and P, and air is admitted through the latter to the train pipe and brake cylinder, thereby producing a rapid application of the brakes throughout the train.

The compressed-air brake. In its simplest form the compressed-air brake consists of a reservoir (in which compressed air is stored), a brake cylinder, an operating valve, and a train pipe. The brake cylinder is of the single-acting type, and is shown in Fig. 301.

The brakes are kept " off " by springs in the brake cylinders acting against the pistons, while they are applied by admitting compressed air, from the reservoir, to the back of the pistons, the force of the application depending upon the quantity of air admitted to the brake cylinders. The brakes are released by exhausting the air from the brake cylinders.

When this brake is used on trains consisting of several coaches, additional features are required in order to obtain quick action of the brake throughout the train. These features are shown in Fig. 301. Each coach is equipped with a brake cylinder, an auxiliary reservoir, a "triple valve," and a "train pipe" (to which the triple valve is connected); while the motor coaches are equipped, in addition, with a compressor, a main reservoir, and the operating (or driver's) valve.

The train pipe is continuous throughout the train, and is connected to the driver's valve, to which is also connected a pipe from the main reservoir, and a connection to the atmosphere.

The main reservoir pipe is also continuous throughout the train, and it connects the main reservoirs to the compressors. Each coach of a motor coach train must, therefore, be provided with two hose couplings at each end (see Fig. 288).

The driver's valve is of the rotary type, and can connect (1) the train pipe to the main reservoir, (2) the train pipe to atmosphere; while it can also cut off the connection between the train pipe, the main reservoir, and atmosphere.

The function of the triple valve is to admit air from the auxiliary reservoir to the brake cylinder, this operation depending upon the *difference* of pressure between the auxiliary reservoir and the train pipe. When the pressure in the auxiliary reservoir exceeds that in the train pipe (such as would happen if the driver's valve connected the latter to atmosphere) the triple valve admits air to the brake cylinder and the brakes are applied. On restoring the pressure in the train pipe (e.g. by connecting it to the main reservoir), the triple valve releases the air in the brake cylinder and charges the auxiliary reservoir.

In order to secure a quick release after an application of the brakes, the pressure in the auxiliary reservoirs is about 20 lb. per sq. in. lower than the pressure in the main reservoir (which is between 80 and 90 lb. per sq. in.). With normal applications of the brake it is necessary to discharge the air gradually from the train pipe and to stop the exhaust gently. This is accomplished by means of an equalizing piston in the driver's valve, in conjunction with a small reservoir (called the equalizing or brake valve reservoir). The equalizing piston controls the exhaust valve (in the driver's valve) for the train pipe, and is operated by the difference of pressure between the brake valve reservoir and the train pipe. The driver's valve is constructed so that for *normal applications* of the brake, the air is exhausted from the brake valve reservoir, and by means of the equalizing piston a corresponding reduction of pressure is obtained in the train pipe.

The *gradual* reduction of pressure in the train pipe causes the triple valves to admit air gradually from the auxiliary reservoirs to the brake cylinders, so that the brakes are applied gradually throughout the train.

When a *rapid application* of the brakes is required in cases of emergency the driver's valve is arranged to exhaust air directly from the train pipe, thereby producing a *sudden* reduction of pressure. Under these conditions the triple valves admit air from *both* the train pipe (through a check valve) and the auxiliary reservoirs to the brake cylinders, so that a rapid application of the brakes occurs throughout the train.

With the above forms of the compressed-air brake a reduction in the

braking effort (after the brakes have been applied) can only be obtained by *fully releasing* the brakes and re-applying them. This disadvantage has recently been overcome by the introduction of a **variable release device,*** by means of which the release of the air from the brake cylinders is under control, so that the brakes can be *partially* released.

* For details of the variable release air brake, see *The Electric Journal*, vol. 10, p. 130, article on "The Electric-Pneumatic Brake System."

CHAPTER XVII

ELECTRIC LOCOMOTIVES

General Considerations

General classification. Long-distance main-line traffic involves high operating speeds and the running of various types of rolling stock, such as restaurant and dining cars, sleeping saloons, corridor and non-corridor coaches, brake vans, etc. Such traffic is best handled by locomotives. Moreover, on a large railway system there are two other classes of traffic for which locomotives are necessary, viz. (1) local passenger traffic, intermediate between suburban and long-distance traffic; (2) freight or goods traffic (with which must be included the marshalling and shunting operations).

Thus a large railway system will require at least three classes of locomotives, viz. (1) "express passenger" locomotives, capable of giving large outputs (1000–2000 h p.) at high speeds (60–90 ml.p.h.); (2) "local passenger" locomotives of moderate output; (3) "goods" locomotives, giving large outputs at slow speeds. In addition, a few "shunting" locomotives will be required for working the marshalling yards and large sorting sidings.

Mechanical design. The mechanical design of an electric locomotive involves many considerations, some of which are external to the locomotive and others are concerned with the operating requirements. The former include the loading and track gauges, the strength of the permanent way, and the strength of the couplings and draw-gear of the rolling stock. Moreover, the wheel arrangement and the disposition of the various parts of the locomotive must be considered with reference to the wear and the cost of maintenance of the permanent way.

The operating requirements concern the draw-bar pull and speed, the weight to be carried on the driving axles, the running qualities, and the cost of maintenance of the locomotive itself.

External considerations. (1) The **loading gauge** affects both the overall width and height of the locomotive. When overhead collectors are employed the lowest operating position of the collectors must be within the loading gauge, and the height of the roof must be arranged accordingly.

The **track gauge** affects the overall length of the motor, and the effect of this limitation on the output is discussed in Chapter IV.

(2) The **strength of the permanent way** limits the maximum load which can be carried on each driving axle. In this country the limit is about 20 tons, but in America axle loads up to 25 tons are permissible on some of the large trunk railways.

The strength of bridges limits the number of driving axles carrying limiting loads and the total wheel-base over which these loads are distributed. In this country, under steam locomotive conditions, the limiting axle load (20 tons) may be carried on each of three driving axles having an overall wheel-base of 14 ft.

(3) The **strength of the couplings and draw-gear** limits the maximum

draw-bar pull. With the passenger rolling stock in use on our main line railways the draw-bar pull at starting must be limited to about 16 tons. But with goods trains in this country the draw-bar pull must be limited to about 12 to 14 tons, on account of the large number of privately-owned wagons in use.* When specially built wagons are employed, the limiting value of the draw-bar pull can be raised to about 30 tons.

(4) The **wear and maintenance of the permanent way** is affected by a number of features, such as traffic density, wheel arrangement, size of driving wheels, height of centre of gravity of locomotive, etc. Generally, for a given traffic, the track wear and maintenance will be reduced if the locomotive has a leading bogie, driving wheels of medium to large diameter, a high centre of gravity, and a minimum of dead, or non-spring-borne, weight on the axles.

Operating requirements. (1) The **draw-bar pull** required in a given case can be estimated when the weight of the train, the acceleration, the gradient, and the train resistance are known.

(2) The **total weight to be carried on the driving wheels** (called the "**adhesive weight**") is determined by the condition that the locomotive shall exert the required tractive effort without slipping the wheels.

The ratio of the tractive effort to slip the wheels and the adhesive weight is called the "**coefficient of adhesion,**" the value of which is influenced by the condition of the rails and also by the speed.

Average values of the coefficient of adhesion at various speeds are—

Speed m.p.h. . . .	0	10	20	30	40	60
Coefficient of adhesion .	0·25	0·18	0·14	0·12	0·1	0·09

Under normal starting conditions, with clean, dry rails, a value of 0·25 may be assumed for the coefficient, and a maximum value of 0·3 when sand is used. If the rails are wet or greasy, the coefficient of adhesion will be much lower; for example, with a thoroughly wet rail a value of 0·18 to 0·2 is usually assumed, while for a moist or greasy rail the coefficient is of the order of 0·15. But with the application of sand these values may be increased to about 0·25.

If the tractive effort fluctuates during starting, the maximum value of the tractive effort must not exceed (adhesive weight × coefficient of adhesion). Hence the more uniform the tractive effort during the starting and initial accelerating periods the heavier will be the train which can be operated by a locomotive of given adhesive weight. This point is of considerable importance for goods traffic, where the weight of the train usually approaches the maximum weight which can be handled by the locomotive.

(3) The **running qualities** are influenced by the wheel arrangement, the height of the centre of gravity, and the disposition of the masses of the various parts with respect to the longitudinal and transverse axes of the locomotive. Good running qualities are characterized by freedom from vibration and oscillations at all speeds. These qualities are obtained by a symmetrical disposition of the masses about the longitudinal and transverse axes of the locomotive, a moderately high centre of gravity,

* The usual type of coupling on wagons is tested to 50 tons, and a factor of safety of 4 is usually allowed.

dynamic balancing of the rotating parts, and, for high-speed working, a guiding bogie. Without these features trouble is usually experienced at moderate and high speeds, due to transverse oscillations (termed " nosing ") of the locomotive between the track rails, causing " spreading" of the latter on account of excessive lateral pressure from the wheel flanges.

Speed-torque characteristics. In all electric motors operating at *constant voltage* (and constant frequency in the case of alternating-current motors) the speed and torque are intimately connected with each other, as has been discussed in Chapters IV, V, VI. With series motors the speed increases as the torque decreases, and large variations of torque produce large variations in speed. On the other hand, with shunt and induction motors the speed is almost unaffected by variations of torque.

Such characteristics are unsuitable for traffic requirements and do not compare favourably with those of steam locomotives, in which, by regulation of the cut-off, the speed and tractive effort are almost inversely proportional to each other (i.e. the output is constant) over a wide range.

More favourable characteristics, however, can be obtained with electric locomotives having series motor equipments by voltage and field control. For example, with single-phase locomotives, regulation of speed over the whole range is effected by voltage control. In this case the speed-output characteristic is governed by limitations of heating and commutation, the permissible output increasing with the speed until the maximum value (as governed by the prescribed limitations) is reached. Fig. 65 (p. 113) shows the speed-output characteristic for one of the motors of a modern single-phase locomotive.

Again, with direct-current locomotives dynamical characteristics somewhat similar to those of steam locomotives can be obtained by the combination of double series-parallel and field control when three or more weakened field steps are provided. In this case, for a given combination of the motors, when the speed is controlled by field weakening, the permissible torque—as governed by limitations of heating and commutation—varies approximately inversely with the speed, and therefore the permissible output is approximately constant over the operating range for this combination of the motors.

Power plant. In general, the main power plant of a locomotive may consist of either one or two motors of large output or a number of motors of moderate output. The number of motors to be employed in a given case depends largely upon the power required, the method of speed control, and the system of power transmission. For example, with single-phase equipments duplication of the motors for purposes of speed control is unnecessary, and a single motor may be employed if the operating conditions are suitable. Similarly, with three-phase equipments, a single motor could be employed under suitable conditions, as four speeds could be obtained by two pole-changing stator windings. But two motors are necessary if cascade control is to be employed. On the other hand, with direct-current equipments, in which the motors are wound for the line voltage, two motors are necessary for series-parallel control and four motors for double series-parallel control. With high-voltage equipments, in which each motor receives a fraction of the line voltage, a corresponding increase in the number of motors is necessary. Thus, in general,

single-phase locomotives may have either a single motor or two, or more, motors; three-phase locomotives have usually two motors; direct-current locomotives with double series-parallel control must have at least four motors, and in some cases (e.g. 3000 volts) six, eight, or twelve motors may be necessary.

Power transmission. The driving axles may be driven either individually or collectively, the power being transmitted from motors to axles, either directly or through gearing. The individual axle drive is usually preferred when three or more motors are available, and the collective drive is employed with a single motor or with two motors. In some cases, when the adhesive weight must be distributed over a long wheel base, a distributed collective, or group, drive is employed, groups of two or three axles being coupled and driven by a single motor or a pair of motors.

The individual axle drive may be applied in a number of ways, according to whether the motors are axle mounted or frame mounted, and also whether a geared or a direct drive is to be employed. Thus we may have: (1) geared axle-mounted motors, (2) geared frame-mounted motors, (3) geared frame-mounted twin motors, (4) gearless bipolar motors with armatures direct on axles, (5) gearless frame-mounted motors.

The collective and distributed-collective drives may also be applied in a number of ways, some of which are direct drives with and without jack-shafts, and others are geared drives.

Each method will now be considered individually, and its limitations and applications will be discussed.

(1) **Individual axle drive with geared, axle-mounted motors.** This method is commonly employed for slow- and moderate-speed locomotives. The motors are arranged and mounted in a manner practically identical with that employed with motor-coach trains. But if motors of 300 h.p. and upwards are necessary, twin gearing (p. 68) is usually fitted.

This method of power transmission involves relatively large dead, or uncushioned, loads on the driving axles, and is, in consequence, unsuitable for high speeds. It has an extensive application to freight locomotives, and also to "light" passenger locomotives for which the maximum speed does not exceed about 50 ml.p.h.

(2) **Individual axle drive with geared, frame-mounted motors.** In this case, due to the motors being mounted on the spring-supported frame of the locomotive, the distance between a given armature shaft and the corresponding driving axle is not necessarily a fixed quantity. Moreover, the axle may not always be parallel to the armature shaft. Hence each gear-wheel must be mounted on a shaft, which must be carried in bearings on either the motor or locomotive frame, and a flexible connection must be provided between this shaft and the driving axle.

In one method (called the **quill drive**) the shaft on which the gear-wheel is mounted is hollow, and surrounds the axle with sufficient clearance to allow for the vertical play of the latter. This shaft, or quill, is carried in bearings integral with the motor frame (Fig. 33), and is, therefore, always parallel to the armature shaft.

The torque may be transmitted from the quill to the driving axle by either spiral springs or a special coupling. As, however, the geared quill drive is usually employed with twin motors—which, for this drive, give a

more favourable design than single motors—it will be considered more in detail in the following section dealing with individual axle drives with twin motors.

In the other method (called the **quilless linkwork drive**) the gear-wheel is connected to the driving wheel by a universal linkwork coupling. The gear-wheel is arranged *outside* the driving wheel and is carried by a stub shaft or pin fixed to the framing of the locomotive. Hence, as the motor is also supported from this framing, the shaft carrying the gear-wheel is, except for distortion of the framing, if any, always parallel to the armature shaft.

This form of quilless drive with outside gear-wheel has been developed by both the Brown-Boveri and Oerlikon Co.s.* It has been applied on an extensive scale by Brown-Boveri to both direct- and alternating-current express passenger locomotives, which are in service in eight countries.

Fig. 302 shows the general arrangement of the **Brown-Boveri linkwork,** which consists essentially of four links. Two of these are in the form of toothed segments and are pivoted in bearings in the gear-wheel. The other links connect the remote ends of the segments to spherical pins, fitted to the driving wheel. The pinion is spherically seated in a hub fitted with springs (as shown in Fig. 303), which damp any irregularities or pulsations in the torque at the motor shaft. This shaft is extended and is supported by an outboard bearing, in addition to the armature bearings in the end shields.

The linkwork is so designed that parallel movements of the driving axle with respect to the gear-wheel shaft do not affect either the uniformity in the transmission of torque, or the constancy of the ratio of the angular velocities of gear-wheel and driving wheel. Oblique movements cause slight deviations in each case.

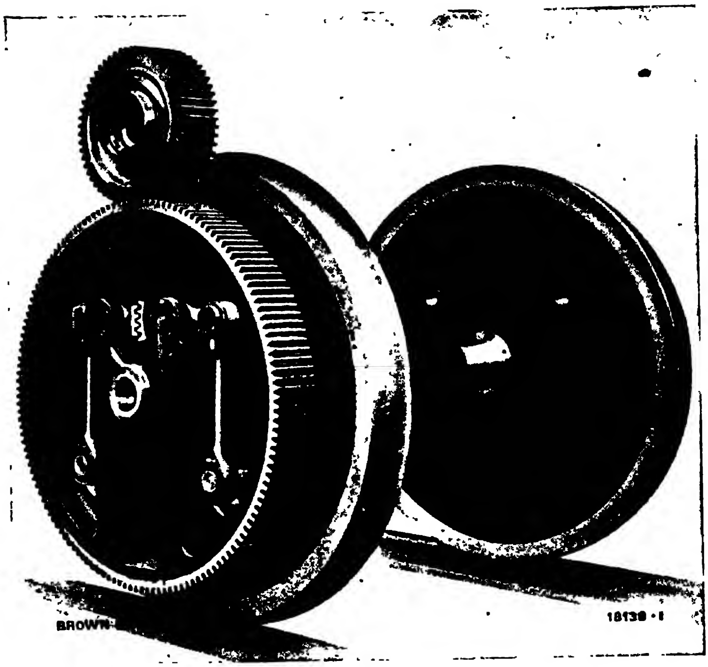
The transmission gear is enclosed in an oil-tight casing and is lubricated by forced circulation of oil. Fig. 304 shows details of the lubricating system. The lowest part of the gear-wheel rim is submerged in an oil bath, and, when running, the oil is thrown against the side walls of the casing and fills one or other of the oil wells *a*. The oil, after passing through a strainer, is conveyed by the pipe *c* to a small oil pump *d*, which is of the two-cylinder eccentric type with ball valves, and is driven from the gear-wheel. The oil is delivered through a hole in the stub shaft to the bearing of the gear-wheel, from which a portion is conveyed by channels to the bearings of the toothed segments and thence to the knuckle ends of the links, and the remainder is conveyed by pipes to the spherical bearings at the other end of the links.

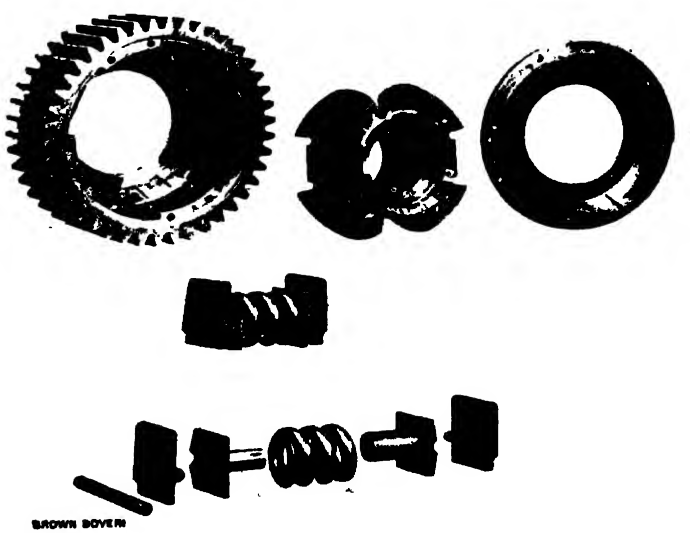
The springs and other internal parts of the pinion are lubricated from the reservoir *s*. Priming of the pump is effected, when necessary, by means of the pipe *q*.

Express passenger locomotives with this form of individual-axle drive have given very satisfactory results in service. Monsieur H. Parodi, in a paper on the electrification of a section of the Paris-Orléans railway,†

* The Oerlikon drive was developed for three-phase motor coaches in which a single frame-mounted motor formed the driving unit; the arrangement being similar (except for the system of power transmission) to that shown in Fig. 299. The coupling was similar to that illustrated in Fig. 306, which, however, refers to a quill drive.

† *Journal, I.E.E.*, v. 64, p. 908.





FIGS. 302, 303.—Brown-Boveri Linkwork Drive and Details of Spring Pinion.

gives records of the vertical, transverse, and combined longitudinal and rolling displacements obtained at high speeds (120 kM.p.h. = 75 ml.p.h.) and comments thus on the running of the locomotive—

With a locomotive fitted with outside-gear drive and weighing 116 tons, we have been able to haul between Paris and Etampes a 650-ton train at 120 kM. per hour, and at this speed the locomotive runs with a smoothness comparable with that obtained with the best bogie coaches.

(3) **Individual axle drive with geared frame-mounted twin motors.** This form of drive (in which each driving axle has a pair of motors geared

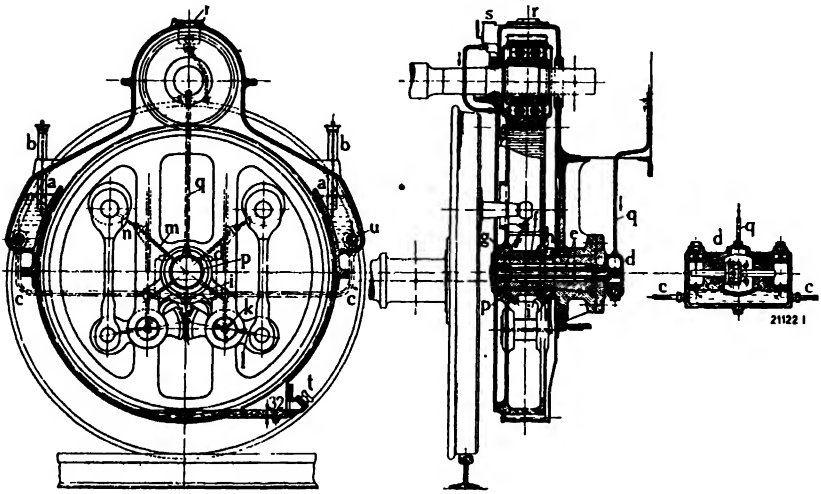


FIG. 304. -Method of Lubricating Brown-Boveri Linkwork Drive.

to it, the pinions meshing with a common gear-wheel) was originally developed by the Westinghouse Co. for single-phase locomotives to enable two motors to be connected permanently in series, in order to obtain, for a given output at the axle, higher voltages and smaller currents in the main circuit compared with those of a single motor of the same aggregate output. Moreover, for a given wheel diameter, track gauge, and gear ratio a greater output can be obtained at the axle with a twin motor than with a single motor.

The drive with twin motors is now employed by a number of manufacturers. It is usually applied with the armature of each twin motor arranged side by side and, in many cases, built into a common frame (Fig. 33). But recently a tandem arrangement of the motors has been developed which possesses certain advantages over the usual arrangement.

The twin-motor is particularly desirable for high-voltage direct-current equipments when two motors have to be connected permanently in series. In this case, since both armatures are mechanically coupled together by the common gearing, the voltage applied to a twin motor is always divided equally between the armatures. On the other hand, if separate series-connected motors driving individual uncoupled axles

were employed, there would be a possibility, should slipping of the wheels of one axle occur, of one motor receiving more than its normal voltage.

In practice, both the "inside" and "outside" positions of the gear-wheel, relatively to the driving wheel, are employed. With the "outside" position of the gear-wheel a universal linkwork coupling, similar to that (Fig. 302) for the corresponding drive with a single motor, must be employed.

With the "inside" position of the gear-wheel a quill drive is necessary, In this case the driving wheels are connected to the quill either by springs or by a universal coupling, the former arrangement being due to the Westinghouse Co. and the latter to the Oerlikon Co.

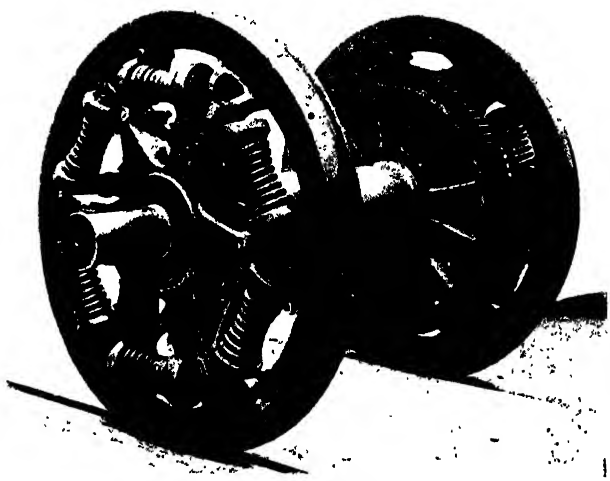


FIG. 305.--Westinghouse Quill Drive.

In the **Westinghouse quill drive** (Fig. 305) the driving springs fit between certain spokes of the wheels and spring-cap brackets fitted to the flanges at each end of the quill. The springs, in addition to transmitting torque, tend to maintain axle and quill concentric, but they allow relative vertical and limited oblique motions (due to irregularities in the track) to occur between these parts. When axle and quill are concentric, one half of the springs on each side are in compression and the other half are in tension.

The **Oerlikon quill drive** with universal coupling has been developed in two forms, one having the coupling outside the driving wheel, and the other having the coupling between the driving wheel and the motor. The former arrangement is employed for standard and narrow gauge locomotives, and the latter has been developed for broad gauge locomotives with large driving wheels, in which sufficient axial space is available between the wheel hubs to accommodate motors, gearing, and coupling.

The "outside" form of coupling is shown in Fig. 306, this illustration referring to an example in which couplings are fitted at both ends of the quill. The pins *A* are fixed to the quill and project through openings

in the driving wheels to carry the pivoted levers *B*. The inner ends of these levers are connected by a rigid link *C*, and their outer ends are connected by flexible telescopic links *D*, to pins *E*, fixed to the driving wheel. The flexible telescopic links *D* contain volute springs and enable relative movements to take place between driving axle and quill. The ends of these links and the pins connected to them have spherical bearings.

The "inside" form of coupling is shown in Fig. 307. This coupling is totally enclosed and is provided with forced lubrication from two

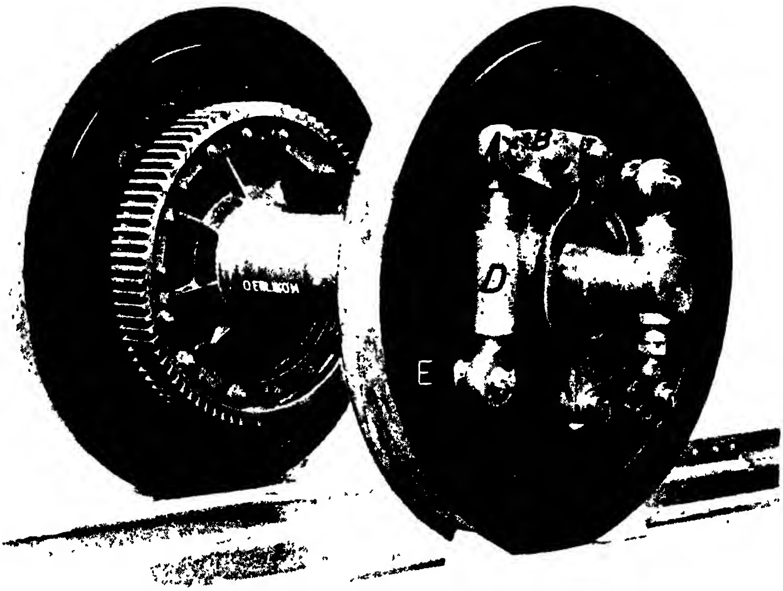


Fig. 306.—Oerlikon Quill Drive with Outside Couplings.

small oil pumps enclosed in the casing. The outer portion of the casing is of cast steel and is integral with the quill. The inner portion, or cover, is completely removable only when the quill is free from the motors, but hand-hole covers are provided for inspection purposes. The coupling proper consists of a quadrilateral frame which surrounds the quill and is constructed in two parts to facilitate dismantling. Pins are fitted at the four corners of the frame. Two of the pins are secured to guide blocks which slide in guides in the casing. The other pins *E* are connected by rigid links *D* to pins *F*, fitted to the driving wheel. These links, and also the portions of the pins connected to them, have spherically-seated bearings to permit the quill to move obliquely with respect to the driving axle.

The torque is transmitted from the quill to the coupling frame by

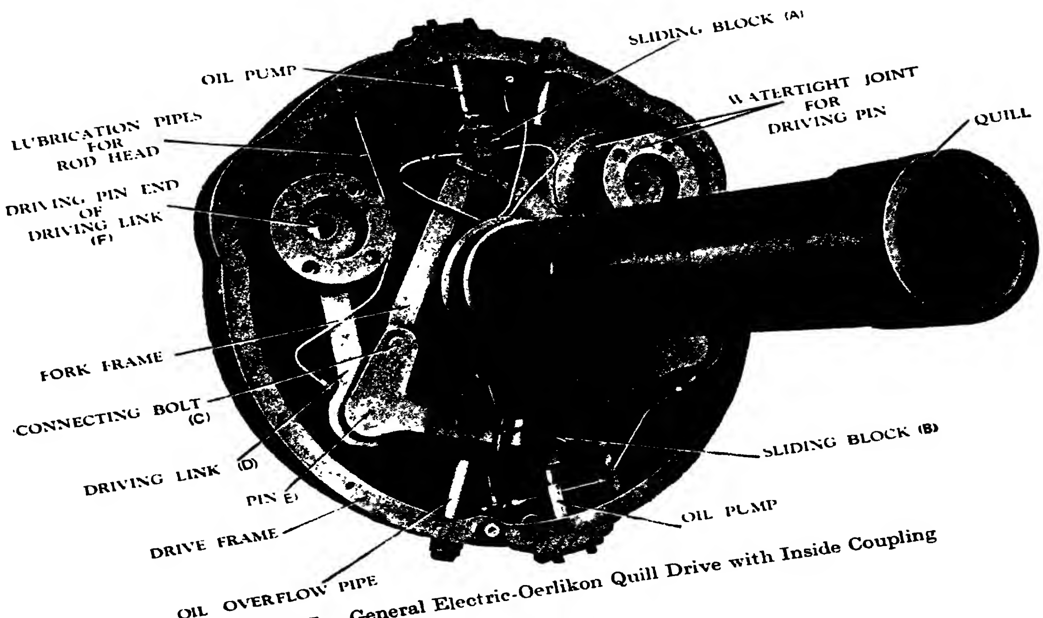


FIG. 307.—General Electric-Oerlikon Quill Drive with Inside Coupling

means of the pins and guides A, B : thence it is transmitted to the driving axle by means of the pins E, F, and the links D. The coupling frame, therefore, rotates with the quill, and relative movements of frame and casing occur only with relative movements between driving axle and quill.

Lubrication is provided by means of two small plunger oil pumps, which are operated by the motion of the coupling frame relatively to the casing, and supply oil, by means of pipes, to the bearings and guides.

The gear-wheel is fitted to the end of the quill remote from the coupling, and laminated springs are inserted between the hub and the rim to absorb shocks due to sudden fluctuations in torque. (Fig. 307A.)

FIG. 307A.—Flexible Gear-wheel. (General Electric Co.)

The twin-motor drive, on account of the frame-mounting of the motors, possesses running qualities equal to those of the individual axle drive with single, frame-mounted motors. It also possesses the advantages that the gear-wheel may occupy either "inside" or "outside" positions; that the width of gear face is only one-half of that required for a single motor of the same aggregate output (other conditions being equal); and that the elements of the twin motor may be permanently connected in series, if necessary, thereby giving, in certain cases, a more favourable electrical design.

With the "outside" position of the gear-wheel the whole width between the wheel hubs can be utilized for the motor, and therefore motors of large outputs are possible. On the other hand, the "inside" position gives a greater choice of gear ratio and armature speed for a given wheel diameter, and usually involves lower gear velocities.

Locomotives with the twin-motor, individual axle drive have been

built by British, Continental, and American manufacturers for large outputs and high speeds. Examples are given later.

The **individual-axle drive with tandem motors** is due to the Swiss Locomotive and Machine Works. The general arrangement is shown in Fig. 308, in which several unique features will be observed. Thus the motors are mounted above the driving wheels; the gear-wheel is mounted upon a short quill and is arranged centrally between the driving wheels, a universal coupling being employed between the gear-wheel and the axle; an intermediate or idle gear (which, if necessary, may form a second

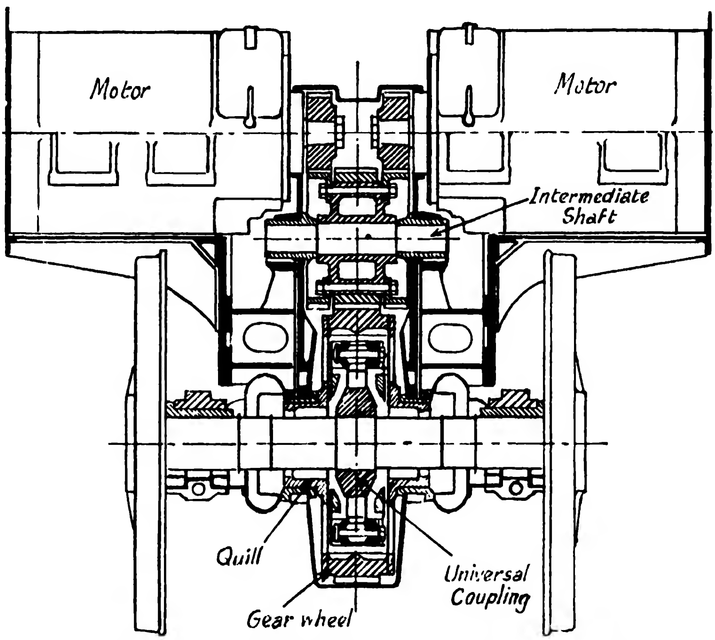


FIG. 308.—Swiss Locomotive Works' Individual-axle Drive with Tandem Motors.

reduction gear) is necessary in the power transmission on account of the relatively large distance between the centres of the armatures and axle.

This drive, while possessing the advantages, enumerated above, of the twin-motor quill drive, possesses a number of advantages over the usual forms of twin-motor quill drives. Thus it can be employed with either "inside" or "outside" locomotive frames; the power is applied to the centre of each driving axle; the whole width of the locomotive framing to the limits of the loading gauge is available for the motors; the size of the driving wheel has no restrictive influence on the design of the motors; there is a large choice of wheel diameter, gear ratio, and armature speed; the motors are located in a convenient position for inspection, and their removal for overhauling or repair is a very simple operation.

(4) **Individual-axle drive with gearless bipolar motors.** This drive was developed by the General Electric Co. (Schenectady) for high-speed

locomotives, of which a number are in service in America. The bipolar design of motor enables the armature to be mounted directly upon the axle, and the full width between the wheel hubs to be utilized for electrical and magnetic purposes. In this manner the armature diameter, for a given output and speed, can be kept relatively small, so that the ill-effects of the unsprung weight are minimized. The field magnets are built into the locomotive frame and the pole faces are almost flat, so that the armature may have vertical play without striking the pole faces. The general arrangement of the motor is shown in Fig. 36 (p. 78), and examples of its application to locomotives are given later.

(5) **Individual-axle quill drive with gearless frame-mounted multipolar motors.** This drive involves the use of a split-frame motor, and is suitable only for moderate and high speeds. It suffers from serious limitations, due to the low armature speed and the restricted space available for the motor. These limitations are of such magnitude as to prohibit the application of the drive to modern locomotives. It is of historical interest to observe that this drive was employed in the original single-phase locomotives of the New York, New Haven and Hartford Railroad, the motors having a 1-hour rating of 240 h.p. Later locomotives were provided with individual-axle drives from geared, frame-mounted motors, both single and twin motors being employed.

(6) **Gearless collective drives.** In these cases the armature shaft of each motor is extended at both ends, and " quartered " cranks (i.e. cranks set at right angles to each other) are fitted to the shaft extensions. The cranks drive coupled wheels on each side of the locomotive by means of connecting rods. In the application of the connecting-rod drive, however, due consideration must be given to the fact that the driving axles have vertical play relatively to the armature shafts. Hence the crank pins of the armatures and driving wheels may only be rigidly coupled if the armature shafts are practically on a level with the driving axles and long connecting rods are employed. In this case the variation in the obliquity of the connecting rods, due to the vertical motion of the driving axle, is small enough to be provided for by the clearances between the axle boxes and guides, so that no additional stresses are produced in the connecting rods. In other cases, either slotted crank-pin bearings must be provided at the driving axle, or an intermediate crank-shaft (called a " jack-shaft ") must be employed, from which a horizontal drive can be obtained for the driving wheels.

The drive with slotted crank-pin bearings at the driving axle usually takes the form shown in Fig. 309, and is called the **"scotch-yoke,"** or **de Kando, drive.** Two motors are necessary, which must be arranged on either side of an axle carrying driving wheels with crank pins. The crank pins on the armature shafts are coupled rigidly together by a triangular framework (called a " scotch yoke "), and the crank pin of the driving wheel is driven from the apex of the framework, a slotted bearing being necessary to provide for the relative vertical movements of driving axle and locomotive frame. The other driving wheels are driven from the centre of the scotch yoke by coupling rods, as shown in Fig. 309.

This drive possesses the advantages of fewer parts and a lighter mechanical construction than the connecting-rod drive in which a

jack-shaft is used, but it necessitates the motors being carried lower on the locomotive framing than in the latter case. This restriction, however, does not present any serious drawback with three-phase, low-frequency motors, and the drive is employed on a large number of three-phase locomotives in which low-frequency motors rated at 1000 h.p. are used with 42-in. driving wheels. But single-phase motors, owing to their larger armature diameters, cannot be mounted in this manner, and in this case gearing must be introduced, the scotch yoke being driven from jack-shafts geared to the armatures.

The scotch-yoke drive has, in practice, been found to require rather a lot of lubrication, and a modified arrangement with jointed links

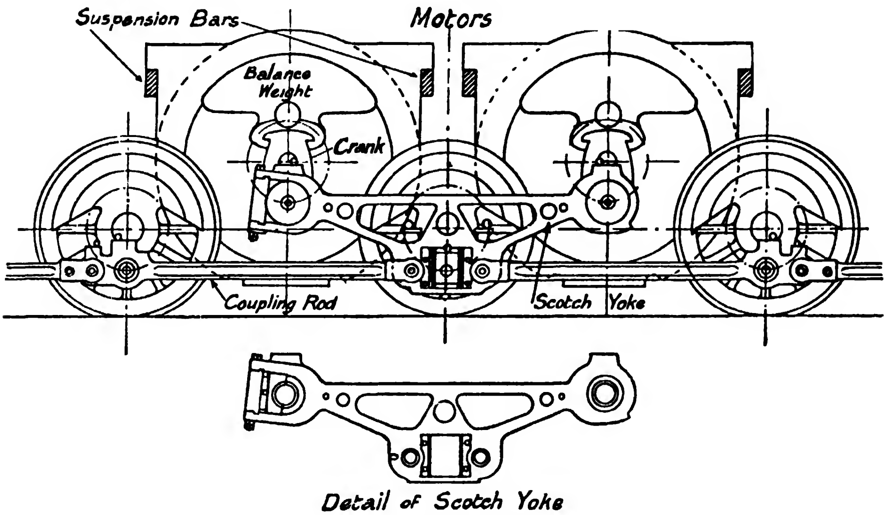


FIG. 309.—Diagram of the Scotch-yoke Drive.

(shown in Fig. 310) has recently been developed by the engineers of the Italian State Railways (on which railways the scotch-yoke drive, in the form shown in Fig. 309, has an extensive application). The inclined rods S_2, S_3 of the new drive have their upper ends connected to a horizontal coupling rod S_1 (which couples together the crank-pins of the motors), and their lower ends connected to levers Z and W. These levers are fulcrumed on the coupling rods K, and are connected by a link L, so as to form a closed linkwork. The complete mechanism is so dimensioned that (1) the principal members S_1, S_2, S_3 form the sides of an isosceles triangle (of which S_1 is the base), the apex of which is, normally, at the centre of the crank pin of the driving wheel; (2) the axis of the link L passes through this point; (3) the arms ec, eg, of lever Z are equal to the arms fd, fh, respectively, of lever W.

In consequence, only the horizontal component of the torque of the motors is transmitted to the driving wheels. Moreover, vertical displacements of the driving axle relatively to the motors cause the inclined rods S_2, S_3 to make equal small angular movements in opposite directions, and to maintain their isosceles arrangement.

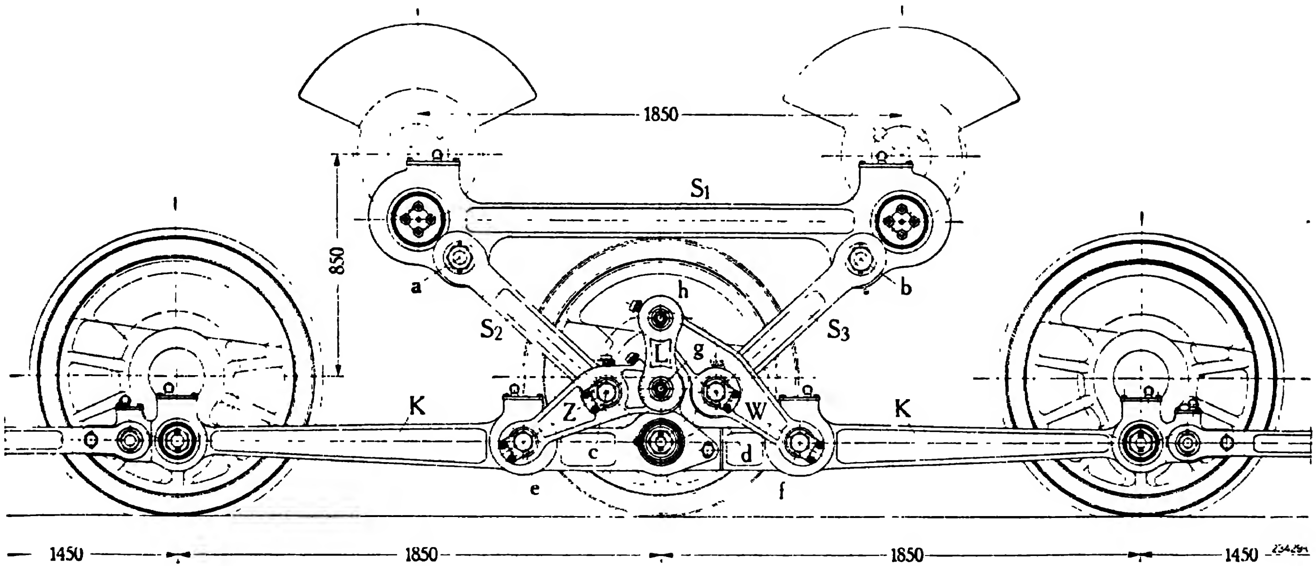


FIG. 310.—Bianchi's Jointed-link Drive for Three-phase Locomotives. (Brown-Boveri.)

It should be observed that with collective drives in which a number of axles are driven through side coupling rods, as in Fig. 309, all the axles must remain substantially parallel under all conditions. Hence, in order that locomotives having five coupled axles may negotiate curves satisfactorily, the outer driving axles must be allowed considerable end-play—from 1 in. to $1\frac{1}{2}$ in., depending on the wheel base and curvature of track—the central axle must either be allowed end-play or be provided with wheels without flanges, and the inner pair of driving axles must have no end-play.

An example of a **connecting-rod drive** in which jack-shafts are employed is shown in Fig. 311, which refers to one of the 4000-h.p., direct-current, 600-volt locomotives in service on the New York terminal lines of the Pennsylvania Railroad. The view shows only the trucks and running gear. The two driving trucks are connected together by a central hinge joint, and the wheel arrangement is similar to that of a steam locomotive, but notwithstanding this feature the running qualities of the electric locomotive proved to be inferior to those of a steam locomotive having the same wheel arrangement. Moreover, the running gear of the electric locomotive required, under service conditions, more frequent attention (e.g. adjustments of the bearing clearances) than that of the corresponding steam locomotives.

This feature, which is common to all side-rod drives with rigid transmission rods, is due to several fundamental differences between the electric locomotive side-rod drive and the steam locomotive side-rod drive. Thus there is no "free end" corresponding to the piston, and consequently the centres between all crank pins must be rigidly maintained. Any wear in the crank-pin bearings or the bearings of the jack-shaft will, therefore, result in excessive stresses and bearing pressures.* In order to avoid excessive vibrations from these causes means must be provided for the accurate adjustment of the bearings. The parts will also have to be designed to withstand the additional stresses due to any incorrect adjustment of the bearings.

Again, the conversion of the uniform torque of the motors into a reciprocating motion produces severe stresses in the motor shaft, jack-shaft, and locomotive framing. For example, since the cranks on the armature shaft are set at right angles to each other, there will be four positions in each revolution where the full torque of the motor is transmitted through one crank. Therefore each connecting rod is subjected to an alternating force having a maximum value represented by maximum value of torque/radius of crank.† Now if the forces acting on each crank pin are resolved in two directions at right angles—one direction being along the line of centres—it will be found that the motor shaft is subjected to reciprocating forces and alternating couples in these directions; the reciprocating forces and couples changing their direction four times in each revolution.‡ These forces act on the motor bearings and frame,

* See an article on "The Crank Drive in Electric Locomotives," by J. Buchli. (*The Electrician*, vol. 73, p. 992; *The Engineer*, vol. 120, p. 287.)

† With single-phase motors the torque is pulsating, and consequently the maximum or crest value must be used in the above expression.

‡ An analytical treatment is given in a paper on "The Electric Locomotive," by Dr. F. W. Carter. *Proc. Inst. C.E.*, vol. cci, p. 231.

Fig. 311.—Trucks and Running-gear of Pennsylvania 4000-h.p., Direct-current, Side-rod Locomotive. (Westinghouse Co.)

and must be taken into account in the design of the machine and the locomotive framing. (Note the rigid frame of the motor illustrated in Fig. 311.)

The jack-shaft will be subjected to greater stresses than the motor shaft, for, in addition to the alternating forces and couples, there is the large twisting moment, due to the transmission of the full power through alternate cranks four times in each revolution. The forces and couples resulting from the connecting rods and coupling rods will depend on the angle between the former and the latter, the maximum values occurring when this angle is 90 degrees, i.e. when the connecting rods are at right angles to the coupling rods. Moreover, the forces at each crank pin can be resolved into a couple and a force, the axis of the couple and the direction of the force both rotating with the jack-shaft.

It is apparent, therefore, that the jack-shaft, the cranks, and the connecting rods will have to be exceptionally strong, while the bearings for the jack-shaft must be liberally designed. In many cases the jack-shaft has a diameter of about 10 in., and special steels are used for the above parts. The mechanical construction of this type of locomotive will, therefore, be more expensive than that of locomotives in which jack-shafts and connecting rods are not used.*

Another feature which is of special importance with side-rod locomotives, is the large forces to which the transmission gear may be subjected when the armature is stopped suddenly, as for instance when the driving wheels are skidded by excessive pressure of the brake shoes, or when a flash-over occurs at the brushes. There are two methods of preventing damage to the transmission gear under these abnormal conditions, viz. (1) to arrange that the armatures shall slip round on their shafts whenever the torque exceeds a predetermined value; (2) to design all the running parts to withstand the stresses under these abnormal conditions. The first method is adopted in the Pennsylvania locomotives (Fig. 311), and has given satisfactory results in practice, except that the mechanical balance has to be readjusted after a slip occurs. The second method, however, is usually preferred in practice, and the mechanical parts are designed with sufficient strength to enable the motors to slip the driving wheels when the coefficient of adhesion is 0·33.

(7) **Geared collective drives.** With all geared collective drives the motors are geared to jack-shafts, from which the wheels are driven by connecting rods. The drive from jack-shaft to wheels is governed by similar conditions to those for the gearless drive.

The gearing enables more favourable armature speeds to be chosen, together with large driving wheels, and its use is particularly desirable with single-phase motors in order to obtain an economical design of motor together with high efficiency and power factor. Moreover, springs can be fitted to the gears for the purpose of damping pulsations and

* In a paper on "Electric Locomotives," Mr. F. Lydall, after discussing the breakages of the connecting rods on some Continental side-rod locomotives, concludes with: "Partly for this reason and also on other grounds connected with the first cost, there is a tendency at present on the Continent towards the use of gearing rather than connecting rods for transmitting the torque to the jack-shaft or direct to the axles. If the author (of the paper) is not mistaken, this is also the general conclusion in the United States, where the connecting-rod drive does not find much favour." (*Journal of the Institution of Electrical Engineers*, vol. 52, p. 384.)

sudden fluctuations in the torque at the motor shaft, and thereby improving the conditions at the jack-shaft.

The geared collective drive is usually employed for single-phase locomotives when slow and moderate speeds are required, and a large number of such locomotives are in service on Continental railways. In some cases geared scotch yokes are used, but more generally some form of connecting-rod drive is employed, typical examples being shown in Figs. 340–345.

Discussion on the limitations of geared and gearless methods of power transmission. With **individual-axle drives** from **geared motors** the size of motor which can be accommodated is limited by both the diameter of the wheels and the track gauge, as explained in Chapter IV. Except in the case of narrow track gauges, however, the limitation imposed by the wheel diameter is not serious, provided that unduly small wheels are not required, as direct-current axle-mounted motors of 450 h.p. can be accommodated with 52 in. wheels. A motor of this rating is the largest size of axle-mounted motor that is desirable in practice on account of the large dead weight on the axle.

When the size of driving wheel and the maximum speed of the locomotive are fixed, the maximum diameter of the pitch circle of the gear-wheel can be obtained by assuming an appropriate value for the limiting gear velocity. This diameter, however, must provide sufficient clearance between the bottom of the gear-case and the track,* which is generally the limiting feature in slow and moderate speed locomotives. The maximum gear ratio and the peripheral speed of the armature can then be obtained when the distance between the centres of axle and armature shaft is known.

For an economical design of motor the peripheral velocity of the armature at the maximum speed of the locomotive should approach the limiting value, viz. 8000 to 10,000 ft. per minute. But the gear velocity must also be within the prescribed limits, which are about 4000 ft. per minute for ordinary lubrication and about 6000 ft. per minute for forced lubrication. The relationship between the peripheral velocities of armature and gearing depends upon the gear ratio, and can be expressed in general terms.

Thus if D_a, D_w denote the diameters of armature and driving wheel respectively, C the distance between centres of armature and axle, V_m the maximum speed of the locomotive in m.p.h., V_a, V_g the corresponding peripheral speeds, in feet per minute, of armature and gearing for the gear ratio employed, we have

$$V_g = 2CV_a/(D_a + D_w V_a/88 V_m).\dagger$$

* For approximate purposes the maximum diameter of the gear wheel may be assumed at about 80 per cent of the diameter of the driving wheel. This value, however, must be considered with reference to the corresponding diameter of the pinion, which may be the limiting feature in some cases.

† This expression is obtained as follows—

Peripheral speed of armature (ft. per min.) at locomotive speed V_m (m.p.h.) and gear ratio (γ) $= V_a = 88 V_m \times \gamma \times D_a/D_w$.

$\gamma =$ diameter of pitch circle of gear wheel/diameter of pitch circle of pinion.

Diameter of pitch circle of gear wheel $= D_w V_g/88 V_m$.

Diameter of pitch circle of pinion $= 2C -$ diameter of pitch circle of gear wheel $= 2C - D_w V_g/88 V_m$.

[*Continued*]

Hence the gear velocity corresponding to the maximum speed of the locomotive depends upon: maximum peripheral speed of the armature, diameter of armature, size of driving wheel, and distance between centres of armature and axle. By proper choice of the size of driving wheel the peripheral speed of the armature can reach the limiting value at the maximum speed of the locomotive, and the gear velocity under these conditions can be kept within the prescribed limits. The geared drive, therefore, enables an economical design of motor to be obtained under all operating conditions.

EXAMPLES. (1) Consider an *axle-mounted motor*, for which $D_a = 29{\cdot}5$ in., $C = 25$ in., to be used with 52 in. wheels for freight service, the maximum locomotive speed being 35 ml.p.h. If the armature is to run at its limiting peripheral speed of 8000 ft. per minute at the maximum locomotive speed, the corresponding gear velocity is

$$V_g = 2 \times 25 \times 8000/(29{\cdot}5 + 52 \times 8000/88 \times 35)$$
$$= 2430 \text{ ft. per minute.}$$

The ratio $V_g/88V_m = 2430/3080 = 0{\cdot}79$, which is just within the limiting value, viz. 0·8. The gear ratio $= V_aD_w/88V_mD_a = 4{\cdot}58$, and the diameter of pinion at pitch circle $= 0{\cdot}79D_w/\gamma = 0{\cdot}79 \times 52/4{\cdot}58 = 8{\cdot}97$ in.†

But if the maximum speed of the locomotive were reduced a corresponding reduction would have to be made in the maximum peripheral speed of the armature, in order to keep the diameter of gear wheel within the limiting value (viz. 0·8 × diameter of driving wheel), as the given diameter of driving wheel is the minimum for this motor.

If the gear ratio is changed to give a maximum locomotive speed of 55 ml.p.h., and the limiting peripheral speed of the armature is to occur at this speed, then

$$V_g = 2 \times 25 \times 8000/(29{\cdot}5 + 52 \times 8000/88 \times 55)$$
$$= 3180 \text{ ft. per minute,}$$

which is well within the prescribed limit for ordinary lubrication. In this case the ratio $V_g/88V_m = 3180/4860 = 0{\cdot}716$. The gear ratio

$$V_aD_w/88V_mD_a = 2{\cdot}9.$$

Alternatively, if a lower gear velocity were desired, the size of driving wheel could be increased. Thus, with 60-in. wheels, a locomotive speed of 55 ml.p.h., and an armature speed of 8000 ft. per minute,

$$V_g = 2 \times 25 \times 8000/(29{\cdot}5 + 60 \times 8000/88 \times 55)$$
$$= 3120 \text{ ft. per minute.}$$
$$V_g/88V_m = 3120/4860 = 0{\cdot}642. \quad \text{Gear ratio} = 3{\cdot}35.$$

(2) In the case of a *frame-mounted motor*, for which $D_a = 24{\cdot}5$ in., $C = 25{\cdot}7$ in., used with 63-in. wheels for a passenger locomotive, for which the maximum speed is 70 ml.p.h.; if the limiting armature speed is 9500 ft. per minute, then

$$V_g = 2 \times 25{\cdot}7 \times 9500/(24{\cdot}5 + 63 \times 9500/88 \times 70)$$
$$= 4000 \text{ ft. per minute.}$$
$$V_g/88V_m = 4000/6160 = 0{\cdot}65. \quad \text{Gear ratio} = 3{\cdot}97.$$

Whence
$$V_a = 88V_m \frac{D_a}{D_w} \times \frac{D_w V_g}{88V_m(2C - D_wV_g/88V_m)}$$
$$= D_aV_g/(2C - D_wV_g/88V_m)$$
or
$$V_g = 2CV_a/(D_a + D_wV_a/88V_m)$$

† The values obtained for the diameter of pinion, gear ratio, and gear velocity may require slight modification in practice when the number of teeth in the gearing and the pitch of the teeth are considered.

If this motor were used, with smaller wheels, on a freight locomotive for which the maximum speed was 40 ml.p.h., the minimum diameter of driving wheel is determined by the condition that the maximum permissible diameter of the gear wheel = 0·8 × diameter of driving wheel. The corresponding value of the gear velocity is, therefore, 0·8 × $88V_m$, and if this value is substituted in the above equation, we obtain

$$D_w = 2{\cdot}5C - 88V_m D_a/V_a$$

Hence, in the present case,

$$D_w = 2{\cdot}5 \times 25{\cdot}7 - 88 \times 40 \times 21{\cdot}5/9500$$
$$= 55{\cdot}2 \text{ in.}$$

$V_g = 0{\cdot}8 \times 88V_m = 2820$ ft. per min. Gear ratio $= V_aD_w/88V_mD_a = 6{\cdot}08$.

Diameter of pinion at pitch circle = 0·8 × 55·2/6·08 = 7·26 in. If this diameter of pinion is too small, a lower limiting armature peripheral speed must be adopted.

With **individual-axle drives** from **gearless motors** in which the armature is mounted directly upon the axle, the full distance between the wheel flanges can be utilized for electrical purposes by adopting a bipolar design, but with a multipolar design or a flexible drive the bearings for the frame will require about 25 per cent of this distance. Hence the bipolar motor will allow of the use of smaller driving wheels than a multipolar machine, thereby leading to a more economical design on account of the higher armature speed.

For example, the bipolar motors of the Chicago, Milwaukee, and St. Paul locomotives (which have a maximum operating speed of 65 ml.p.h.) are rated at 335 h.p., and the respective diameters of the wheels and armatures are 44 in. and 29 in. Hence the peripheral speed of the armature at the maximum speed of the locomotive is 3770 ft. per minute.

With **gearless collective drives** the maximum permissible angular velocity of the crank shafts is about 500 r.p.m. This value may be considered as the limiting value of the angular velocity of the armature, and since the diameter of the armature is not restricted by that of the driving wheels, the limiting peripheral velocity may be made to coincide with the limiting angular velocity. Thus, if the limiting angular and peripheral velocities be assumed as 475 r.p.m. and 7500 ft. per minute respectively, then, for a maximum locomotive speed of 80 ml.p.h., the diameter of the driving wheels will be 56·5 in., and the maximum diameter of the armature will be 60 in. If the maximum locomotive speed is of the order of 50 ml.p.h., a lower value for the limiting angular velocity must be adopted, as the above value will lead to small driving wheels. Assuming the minimum diameter of the driving wheels to be 42 in., then for a speed of 50 ml.p.h. the angular velocity will be 400 r.p.m., and the diameter of the armature, corresponding to a limiting peripheral speed of 7500 ft. per minute, will be 71·5 in.

These considerations show that the sphere of usefulness of the direct drive is limited, and for an economical design of the motor it will be necessary to adopt gearing between the armature and the jack-shaft when the operating speeds are of the order of 50 ml.p.h. and below.

Control and auxiliary equipment—Location and general arrangement. In the general layout of this apparatus on a locomotive it is necessary to arrange that (1) the master controller, auxiliary control switches,

Fig. 312.—Views of Control Apparatus in Cab of Westinghouse 60-ton Direct-current Locomotive.

FIG. 313.—Control Apparatus Compartment of 1500-volt, 1730 h.p. Locomotive. (Oerlikon Electro-pneumatic Control Equipment arranged on each side of a Central Corridor.)

brake valves, and instruments are arranged in convenient positions and do not interfere with the driver's look-out; (2) the contactors and auxiliary machines which require attention are placed in accessible positions; (3) all high-tension apparatus is located in locked compartments which cannot be opened until the circuits are "dead."

With many **low-voltage, direct-current locomotives** the body is constructed with a central cab (which forms the driver's cabin) and two sloping ends. The compressor, blower, master controllers, brake valves, circuit-breakers and switches are located in the central cab; the contactors, reversers, rheostats, and brake reservoirs are located in the sloping ends, the sides of which are removable for the inspection of this apparatus.

In some cases, however, the compressor and blower are located in the sloping ends, and the contactors, rheostats, and other control apparatus are located in the cab. This apparatus is then arranged on a steel structure with expanded-metal screens, and is located in the centre of the cab, so that each part is readily accessible for inspection. The illustrations in Fig. 312 refer to standard 60-ton locomotives of the Westinghouse Co., and provide an excellent example of compactness and accessibility. The control apparatus is of the electro-pneumatic type: the reverser, control-circuit rheostat, and the distributing valve for the air brake are at floor level; the "switch group" and circuit breaker (or "line switch") occupy a central position with the rheostats above. The rheostat compartment is enclosed with sheet steel doors which extend to the roof, and the latter is provided with ventilators, so that an effective circulation of air through the rheostats is obtained. The master controller and the driving position are also shown in the illustrations.

With **high-voltage, direct-current locomotives** the box, or coach, type body is usually employed, and the high-voltage control equipment (contactors, reversers, etc.) is located in compartments along each side of the body. In some cases a central gangway is provided, and in other cases either one or two side-gangways. Two examples are shown in Figs. 313, 314, and further examples are given later in connection with particular locomotives. The rheostats are, in some cases, located above the contactor compartments, but it is generally preferable to locate them in separate, specially ventilated compartments, in order to avoid the heat being communicated to the contactor compartments.

The roof is removable in two or more sections, those portions carrying pantagraph collectors being removable with the collectors as separate units.

Single-phase locomotives, in many cases, have also box-type bodies. The tap-changer (contactors or tapping switch) is usually mounted on, or adjacent to, the main transformer, and the reversers are mounted on the motor frames in order to reduce the length of the heavy-current connections. Moreover, with large frame-mounted motors the blowers are usually mounted on the motor frames, so that no air trunks are necessary.

Practically the whole of the roof is removable in order that the frame-mounted motors, transformer, and other heavy items may be lifted out through the roof. In some cases portions of the sides are also removable, as shown in Fig. 315.

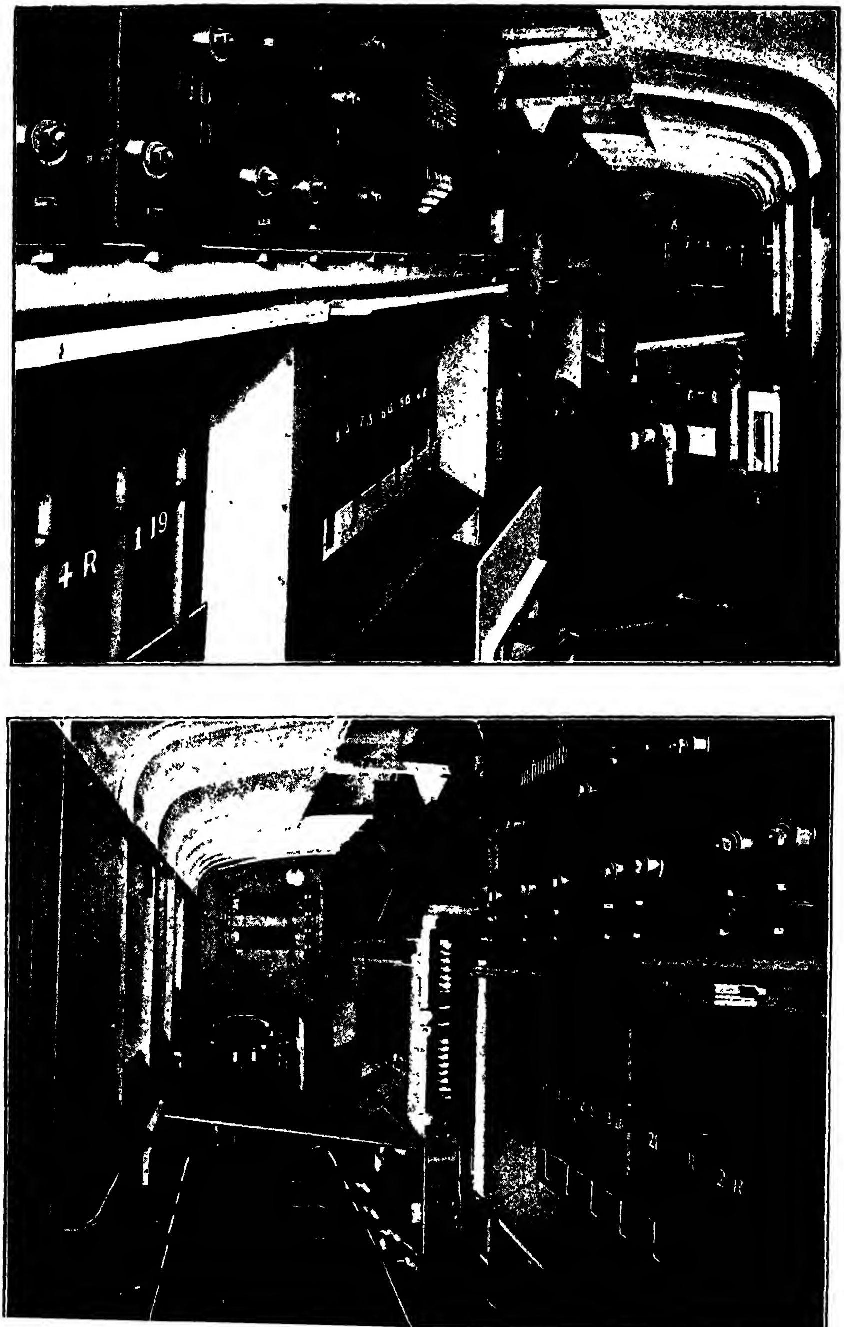


FIG. 314.—Control Apparatus Compartment of 3000-volt, 2340 h.p. Locomotive. (Metropolitan-Vickers Electro-pneumatic Contactors, Cam-operated Group Switches and Reversers.) NOTE.—The Compartment is about 25 ft. long.

EXAMPLES OF ELECTRIC LOCOMOTIVES

The examples which follow have been selected to be representative of modern locomotives. Detailed descriptions of the motors, control and auxiliary apparatus are not included, as examples of this equipment have already been given.

I. Direct-Current Locomotives

Bogie locomotive with geared, axle-mounted motors. Table XII, Reference No. 1,* gives data of a typical locomotive which is in service on the

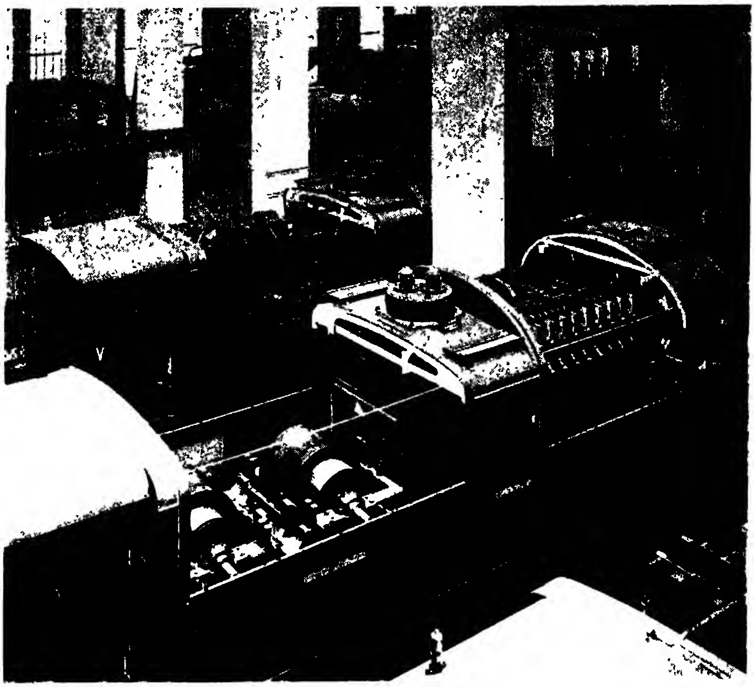


Fig. 315. –Single-phase Passenger Locomotives under construction in Siemens-Schuckert Works.

Metropolitan Railway, London. The body is mounted upon two bogie trucks in the same manner as that of a motor-coach, and the draw- and buffing-gear is built into the underframe. Each truck is equipped with two 300 h.p. self-ventilated motors (with single gearing) and duplicate collector shoes.

The control apparatus, rheostats, and auxiliary apparatus is located in the locomotive body, and is arranged centrally with gangways on each side.

Articulated bogie locomotives with geared, axle-mounted motors. Bogie locomotives of the above type fulfil the requirements for goods traffic in

* The principal dimensions, weights, and other data of the locomotives discussed here are given in Table XII (facing).

this country, since the draw-bar pull must be limited to about 14 tons' on account of the draw-gear on the wagons. Abroad, however, stronger, and in some cases automatic, couplings (wherein the buffing- and draw-gear are combined) are employed in combination, in many cases, with continuous air-brakes. These couplings will withstand safely a draw-bar pull of between 30 to 40 tons, and they, therefore, permit the running of very heavy freight trains, the weight of the train, in some cases, in America, reaching 4000 tons. Under these conditions a very powerful locomotive is required, and, to relieve the underframe and bogie centres from excessive stresses, the buffing and draw-gear must be incorporated with the trucks or locomotive framing, according to the manner in which the motors are mounted. When bogie trucks equipped with motors are adopted, they must be articulated or hinged together in order that the

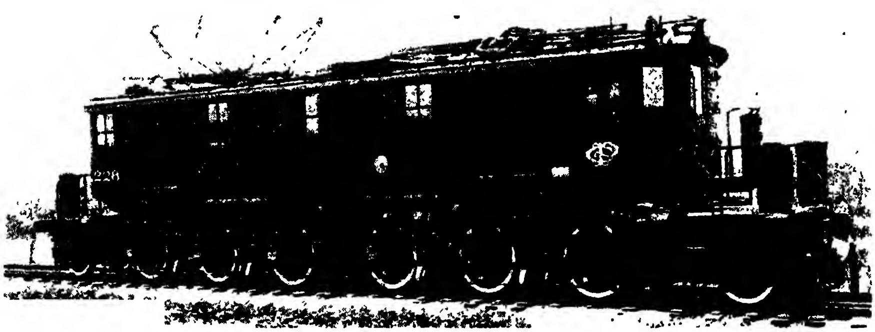


FIG. 316. -Heavy Passenger Locomotive (Paulista Railway) with Geared Axle-mounted Motors.
(General Electric Co., Schenectady.)

tractive effort of the leading truck may be transmitted to the draw-gear. It is apparent, therefore, that the body of the locomotive cannot be connected to both trucks by centre-pins (as in the above locomotive), since the distance between the truck centres will vary with the radiation of the trucks. This difficulty is overcome by the use of a standard centre-pin on one truck and a special centre-bearing on the other truck, this bearing allowing swivelling and longitudinal sliding motions to take place.

Locomotives with these features are shown in Figs. 316, 317, 320, and 323. The locomotive shown in Fig. 316 (Reference No. 2, Table XII) is typical of **American practice.** The trucks have cast-steel "bar" frames, and the axle-box springs of each side-frame are connected together by an equalizing bar in order to equalize the loads on the driving axles.

The locomotives shown in Figs. 317 and 320 are representative of **British practice** and are designed for freight traffic. The trucks are of the "plate" type (being built up from steel plates, steel structural sections and castings) and the axle-box springs of each side-frame are connected together by an equalizing bar.

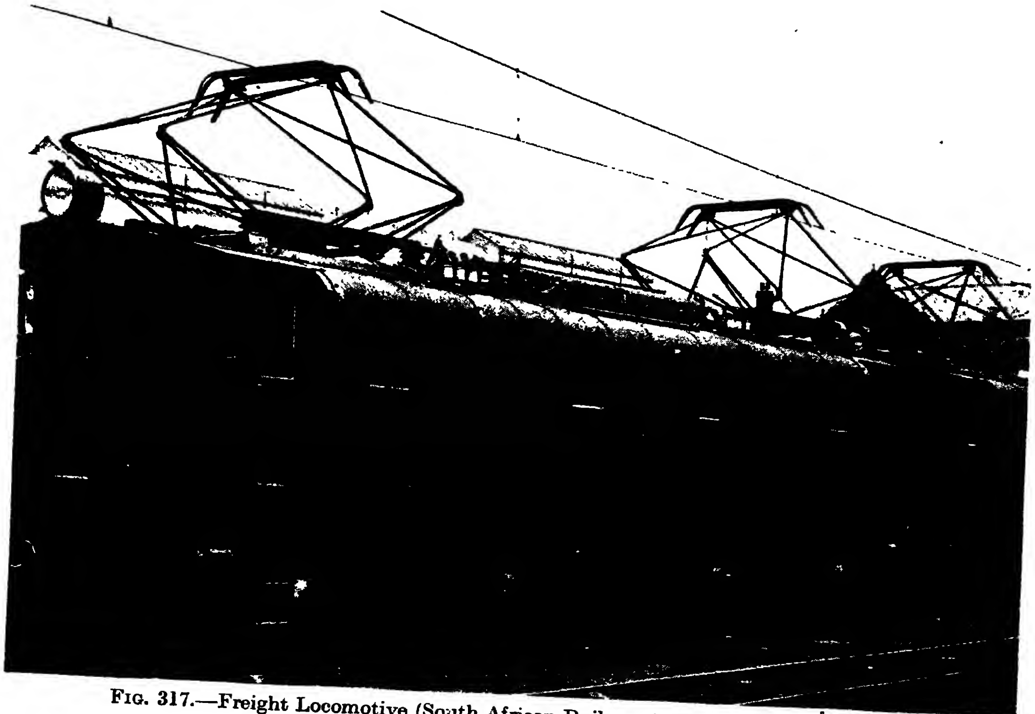


FIG. 317.—Freight Locomotive (South African Railways). (Metropolitan-Vickers.)

A number of locomotives of the type illustrated in Fig. 317 (Reference No. 3) are in service on the **South African Railways** (3 ft. 6 in. gauge, 3000 volts). Certain sections of the line have steep gradients, and freight trains have to be hauled over the entire route.* Traffic arrangements are facilitated by making up the trains to definite maximum loads and employing one, two, or three locomotives per train according to the gradient.

Each locomotive has a weight of 66 tons, and is equipped with four motors, each rated at 300 h.p. (continuous) 1500 volts. The electrical

Fig. 319.—Driving Cab, Auxiliary Machine Room, and Side Corridor of Locomotive illustrated in Fig. 317.

equipment is of the Metropolitan-Vickers electro-pneumatic type, and is arranged for multiple-unit control and regenerative braking. The contactors, reversers, change-over, and group switches are contained in a high-tension compartment, and the auxiliary plant is located at each end of this compartment, as shown in Fig. 318; the arrangement being such as to provide a side corridor giving access to the apparatus from the driving compartments. The door of the high-tension compartment is interlocked with an air valve in the air supply to the two pantagraph collectors, so that this compartment cannot be entered unless the pantagraphs are lowered.

Interior views of the locomotive are shown in Fig. 319.

* A description of the electrification and operating conditions is given by Mr. F. Lydall in a paper on "The electrification of the Pietermaritzburg-Glencoe section of the South African Railways." (*Journ. I.E.E.*, vol. 66, p. 1021.)

The auxiliary power plant comprises two motor-generator blower sets (one rated at 16 kW. and the other 28 kW.), an air compressor, and a rotary exhauster. Both motor-generator sets are driven by 3000 volt, double-commutator motors. The generator of one set operates in parallel with a battery and supplies power, at 100 volts, for control, lighting, and the motors driving the air compressor and exhauster. The generator of the other set provides the excitation of the traction motors during regenerative braking, according to the scheme described on p. 320.

The locomotive illustrated in Fig. 320 is in service in Montreal. It

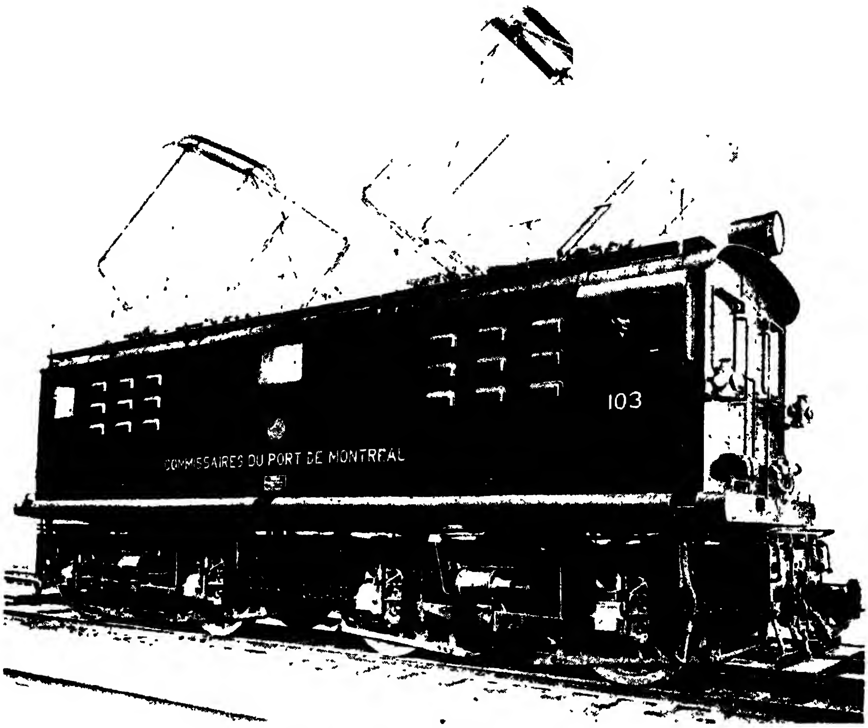


FIG. 320.—Heavy Freight Locomotive.
(English Electric Co.)

weighs 100 tons and is equipped with four 430 h.p. 1200-volt motors with twin gearing, the operating pressure being 2400 volts. Central automatic couplings enable pulls of 30 tons to be exerted at the draw-bar.

The electrical equipment is by the English Electric Co. and, as the locomotive operates over level routes, no provision is made for regenerative braking. The auxiliary power plant is, therefore, simpler than that of the locomotive illustrated in Fig. 317, and comprises a single motor-generator-blower set (viz. a 50 h.p., 2400-volt motor, a 16 kW., 120-volt generator, and two blowers), the generator of which supplies power to two air-compressor motors in addition to the control and lighting circuits of the locomotive.

The control equipment is of the all-electric, cam-shaft, multiple-unit

type, and is located in a compartment along one side of the locomotive, together with chambers containing the isolating switches and circuit breakers. The motor-generator blower set is located along the opposite side, and a central gangway is provided, as shown in Fig. 321. The general arrangement is shown in Fig. 322. The rheostats are contained in compartments on each side of the control compartment, and the normal

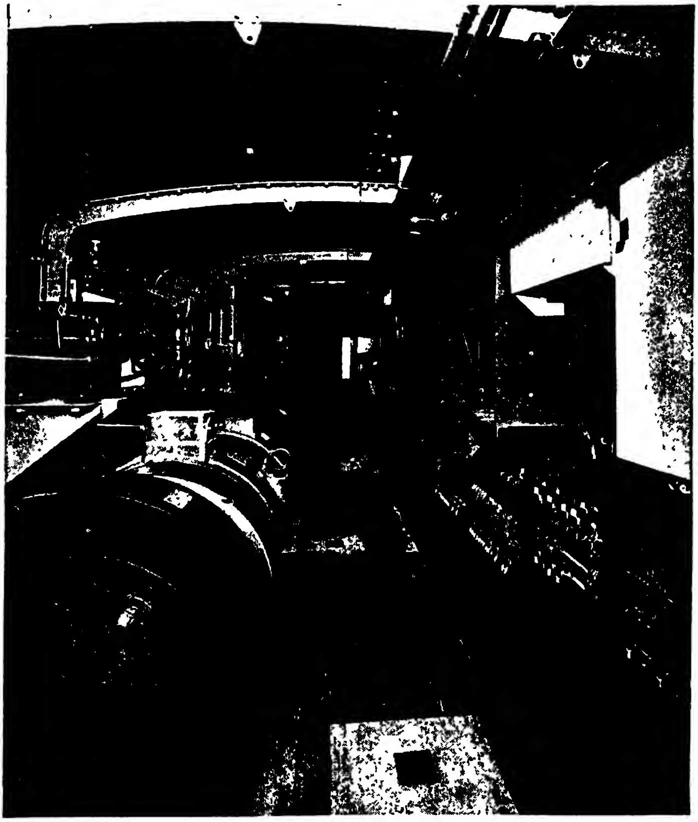


FIG. 321.—Control Apparatus and Auxiliary Machinery Compartment of Locomotive illustrated in Fig. 320.

ventilation is by holes in the floor of the compartments, cowled openings in the roof, and hooded louvres in the outside wall.

On account of the extreme conditions of cold under which the locomotive has to operate, each of the driving cabs is heavily lagged, fitted with double windows, and provided with a 6 kW., 2400-volt heater. Special provision is also made for pre-heating during winter the air supply to the blowers, this air being drawn through the compartments in which the starting rheostats are located. During summer, however, the air is drawn directly through two large openings in the side wall adjacent to the blowers, these openings being closed during winter. Moreover, to avoid

condensation taking place in the motors during cold weather after the locomotive has finished its day's service, means are provided for connecting all the field coils in series and plugging them to a 220-volt supply which is available in the locomotive depot.

To facilitate shunting operations with this locomotive, the driving cab at one end is extended laterally on each side of the body and is fitted with windows fore and aft, as shown in Fig. 320. Master controllers are provided in each of these extensions, so that, altogether, the locomotive has three master controllers.

A further example (Reference No. 4) of the class of locomotive under consideration is shown in Fig. 323. In this case six driving axles are

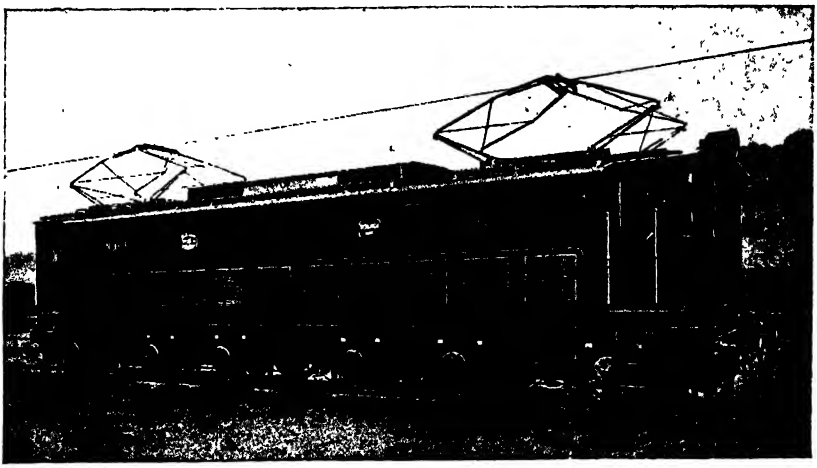


FIG. 323.—Freight and Passenger Locomotive (Spanish Northern Railway) with Geared Axle-mounted Motors (Oerlikon).

employed in order to limit the load per axle to 15 tons. A number of these locomotives are in service on the 1500-volt, broad (5 ft. 6 in.) gauge lines of the **Spanish Northern Railway** for passenger and freight traffic. The one-hour rating (at 1350 volts) is 2040 h.p., the corresponding speed being 20·8 ml.p.h.

The electrical equipment is of Oerlikon manufacture, and the general arrangement is shown in Fig. 324. The motors are axle mounted, forced ventilated, and have single gearing. Under present operating conditions the three motors on each truck are permanently connected in series, and the two groups are controlled on the series-parallel system, provision being made for regenerative braking.

As vacuum brakes are employed on the trains, the auxiliary equipment of the locomotive includes both compressor and exhauster sets; there being one air compressor and three vertical vacuum pumps. Two of the vacuum pumps are coupled to one motor, and this set is employed to exhaust rapidly the air from the brake cylinders, etc., after an application of the brakes, the set being started and stopped by a controller combined with the driver's brake valve. The other vacuum pump is

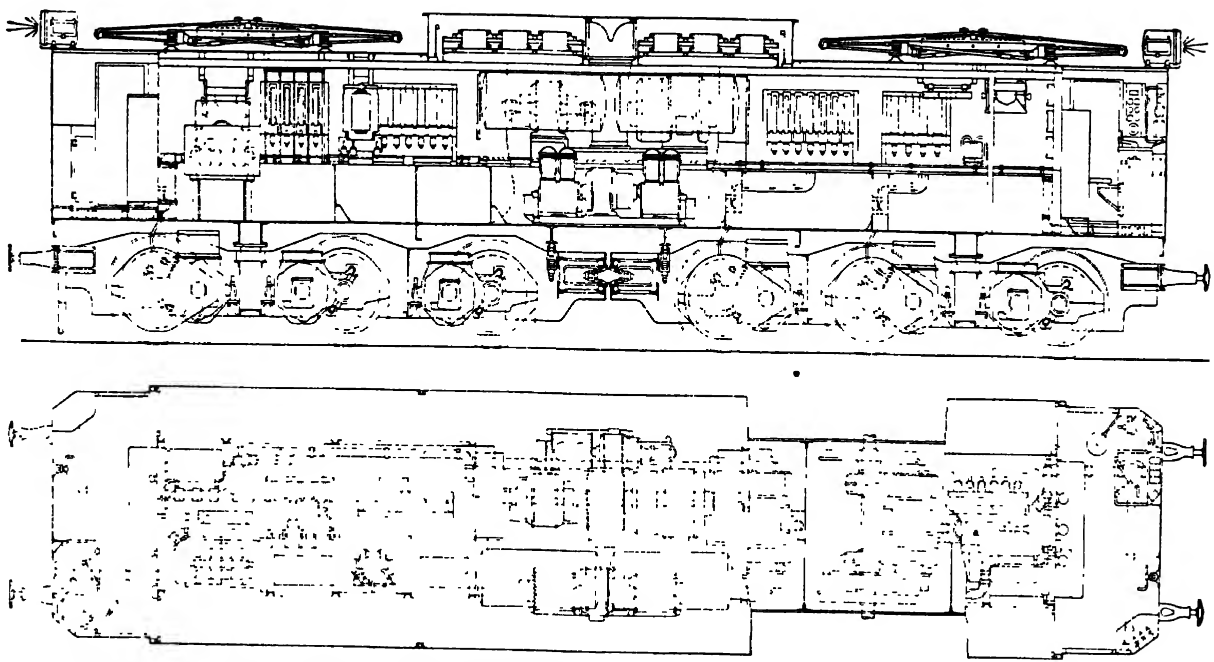


FIG. 324.—General Arrangement of Electrical Equipment on Locomotive illustrated in Fig. 323 (Oerlikon).

coupled to the air compressor, and this set runs continuously. The air compressor, however, is provided with an unloading valve, which comes into operation when the air pressure reaches 100 lb. per square inch. A vacuum regulating valve is also provided for the vacuum pump, and prevents the vacuum exceeding a predetermined value.

The various pipes, valves, etc., necessary in connection with these sets are shown diagrammatically in Fig. 325.

High-speed locomotive with geared, frame-mounted motors. The general arrangement of a locomotive with the Brown-Boveri linkwork drive is shown in Plate II. This locomotive (Reference No. 5) is in service on the **Paris-Orléans Railway,** and is noteworthy on account of the large size of its geared motors. It is capable of hauling heavy trains (500 to 600 tons) at a speed of 80 ml.p.h., and has to traverse curves of 1500 ft. and 500 ft. radius at speeds of 62 and 25 ml.p.h. respectively.

The locomotive differs in several features—other than the arrangement of the motors and the system of power transmission—from those considered previously. Thus (1) the driving axles are fitted to a rigid "plate" frame which is *inside* the driving wheels; (2) leading and trailing bogies, or guiding trucks, are provided, each of which is fitted with a spring centring device to ensure good running qualities at high speeds.

The main framing, which supports the body and the motors, consists of a central portion, constructed of 25 mm. plate, and end portions constructed of 20 mm. plate; the longitudinal plates being connected by cross members which give the requisite stiffness. The end cross members carry the buffers and draw-gear. The central portion of the framing is further strengthened by an auxiliary framing, constructed of 18 mm. plate, which is arranged outside the driving wheels, and is connected to the main framing by steel castings. This (auxiliary) frame carries the stub shafts for the gear wheels (which are outside the driving wheels).

The axle-box springs of the driving axles are of the semi-elliptic type; they are arranged under the axle boxes (as on a steam locomotive), and the springs on each side are connected by pivoted levers to equalize the load between the several driving axles.

The guiding and trailing bogies have "outside" axle boxes, which are fitted with a combination of semi-elliptic and spiral springs.

To enable the locomotive to traverse sharp curves satisfactorily the two inner driving axles each have a total end play of 50 mm., and each bogie is fitted with a spring centring device. Moreover, the pivotal axis of each bogie is displaced from the vertical centre-line by about 150 mm. towards the driving axles.

Each of the four driving motors is rated at 1000 h.p., 1500 volts, and is mounted above the corresponding driving axle, the power being transmitted through twin gearing and Brown-Boveri linkwork.

The control is on the double series-parallel system.

The blowers for ventilating the motors are connected directly to the end-shields of the motors and are driven in pairs, this arrangement being similar to that adopted in Brown-Boveri single-phase, four-motor locomotives. [Fig. 339 (p. 475).]

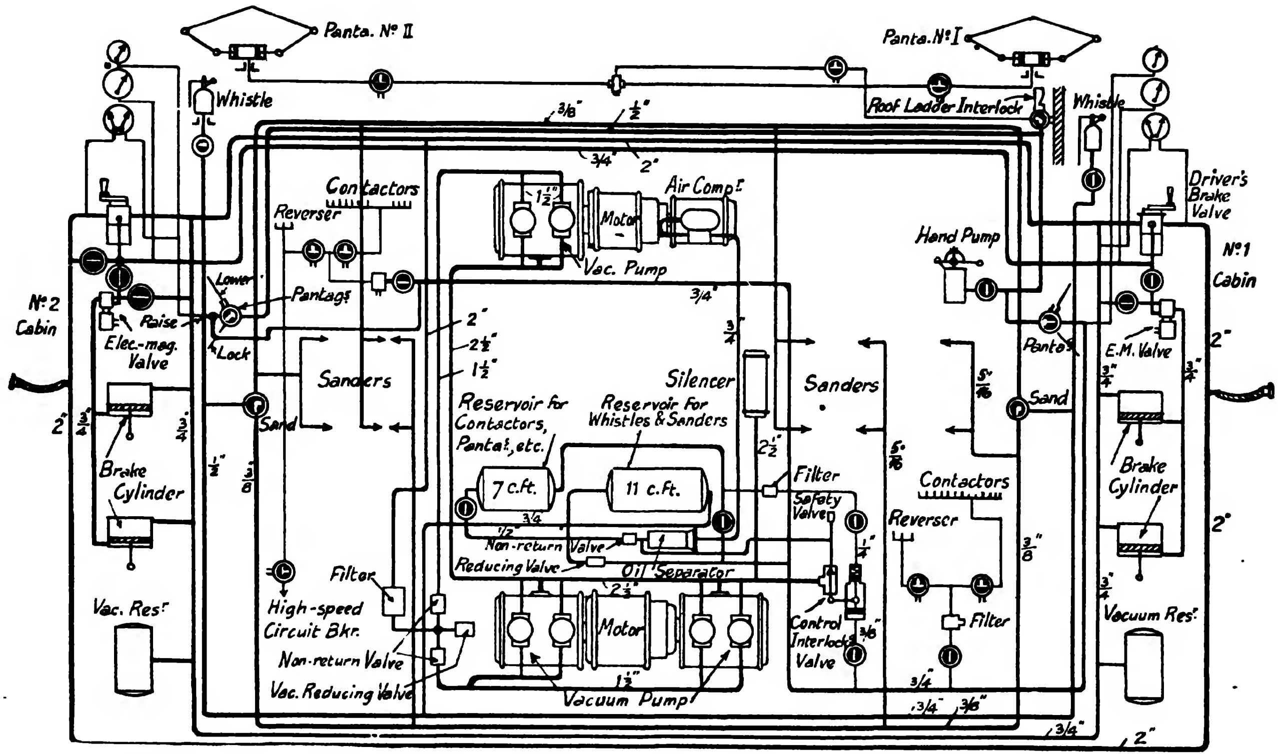


FIG. 325.—Layout of Compressed-air and Vacuum Piping and Apparatus on Electric Locomotive (Oerlikon)

High-speed locomotives with geared, frame-mounted, twin motors. The type of locomotive (originated by the Westinghouse Co.) employing frame-mounted twin motors with quill drive is now in service on several railways (e.g. New York, New Haven and Hartford; Chicago, Milwaukee, and St. Paul; Paris-Lyons-Mediterranean; Great Indian Peninsula).

For high-speed operation the power is transmitted from quill to driving axle by a universal linkwork coupling, two forms of which have been described on pp. 423, 427. The quill drive, however, is not essential with the twin-motor arrangement, as the Brown-Boveri linkwork drive (which was developed originally for frame-mounted single motors) can be applied.

An example of a locomotive with frame-mounted twin motors and the Brown-Boveri linkwork drive is shown in Fig. 326. This locomotive (Reference No. 6) is designed for a maximum speed of 85 m.p.h. and is one of the trial locomotives built for the **Great Indian Peninsula Railway**. It has a plate frame with inside axle boxes, and bogies similar to that of the Paris-Orléans locomotive. Each motor forming part of a driving unit is built with a separate frame, and the two motors of each unit are connected permanently in series. The ventilating air is supplied by two blowers to two air trunks from which connections are made to the inlets in the end shields of the motors.

As **examples of twin-motor equipments with quill drives** the Oerlikon trial locomotives built for the **Paris-Lyons-Mediterranean** and the Great Indian Peninsula Railways may be considered.

Details of construction of the P.-L.-M. locomotive (Reference No. 7) are shown on Plate III. This locomotive is of the articulated double-truck type with guiding bogies. Each truck has two driving axles, each of which is equipped with a twin motor (rated at 665 h.p., 1500 volts) and a quill drive, with the Oerlikon universal coupling.

The central, box-shaped portion of the body is supported from the main trucks by spherical pivotal bearings and spring-borne side bearings, but the sloping ends are fixed to the trucks. The body is constructed with a driving compartment at each end, two side corridors, and central compartments containing the control gear and ventilating plant.

The control gear is of the electro-pneumatic individual contactor type and is arranged for double series-parallel control (with two tapped-field steps for each combination of the motors) and regenerative braking. It is divided into two groups, each group (comprising the control equipment for the motors of one truck) being contained in a separate compartment. These compartments are arranged above the floor level of the body so that the apparatus is conveniently situated for inspection. The space beneath forms an air trunk, from which flexible connections are made to the inlets on the motors. The rheostats are located in compartments adjoining the roof.

The ventilating plant consists of a motor-driven duplex blower with vertical shaft, and is located in a small compartment adjoining the two control compartments. The lower impeller supplies the cooling air (17,000 cubic feet per minute) for the traction motors, and the upper impeller the cooling air (10,000 cubic ft. per minute) for the rheostats.

The auxiliary plant, additional to the blower set, comprises two air compressors and a motor-generator set, the motors of which operate at the line voltage.

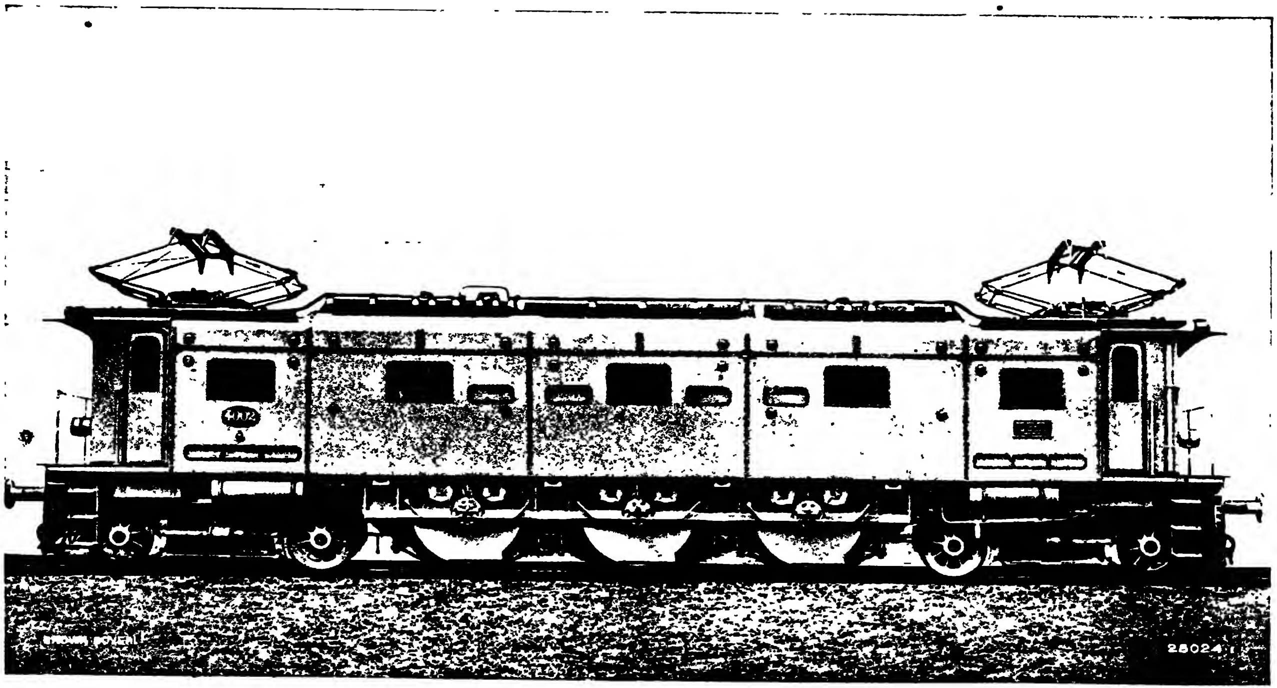


Fig. 326.—Brown-Boveri High-speed Locomotive (G.I.P. Railway) with Twin Motors. (View from Driving Side.)

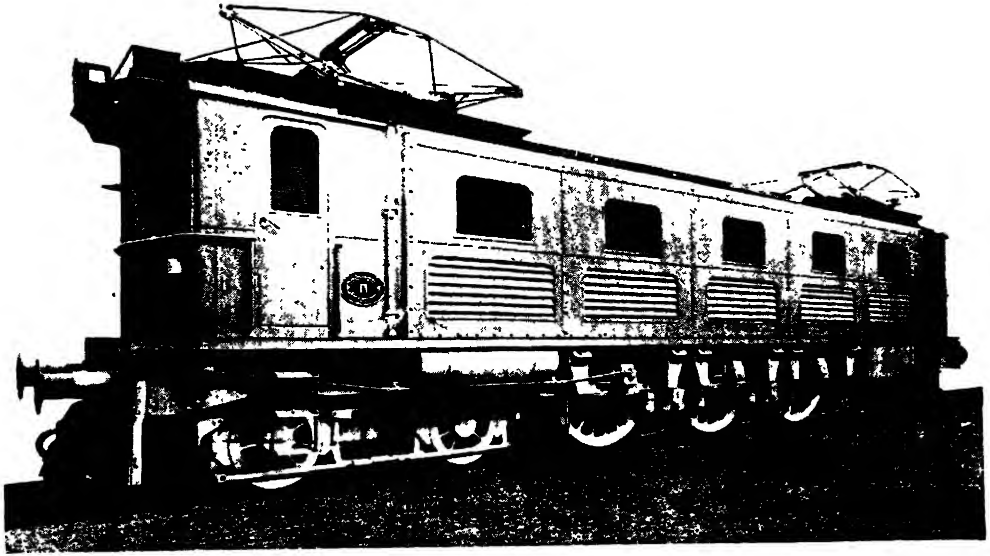


Fig. 327.—High-speed Locomotive (G.I.P. Railway) with Twin Motors and Coupling Drive. (General Electric Co.)

The current-collecting equipment comprises two pantagraphs and eight shoes. The pressure between a shoe and the rail is normally 66 lb., but it may be increased up to a maximum of 440 lb. when the presence of snow and ice on the conductor rail renders such high pressures necessary.

A noteworthy feature incorporated in the control equipment is the interlocking of the air and electric (regenerative) brakes of the locomotive. During recuperation the air brake cannot be applied to the driving wheels of the locomotive, but its application, if necessary, to the other vehicles of the train is unaffected. Moreover, in the event of failure of the electric braking torque—due to the opening of protective relays or any other cause—a gradual reduction of pressure is made automatically in the

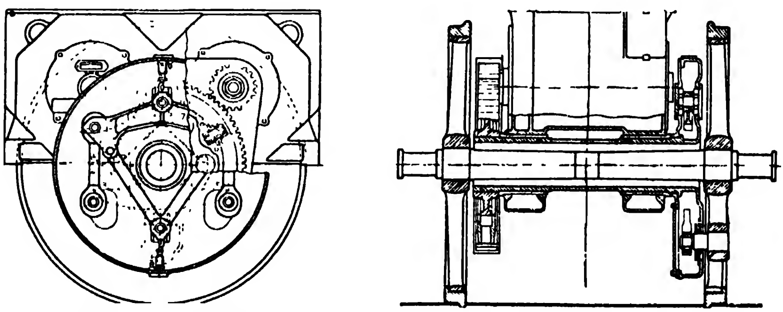


FIG. 328.—Arrangement of Twin-motor and Oerlikon-General Electric Coupling Drive.

train pipe, thereby causing an application of the brakes throughout the train and preventing the possibility of a runaway.

Larger locomotives are of similar general design, but the main trucks have three driving axles, each of which is fitted with a twin-motor rated at 900 h.p., 1500 volts.

The General Electric Oerlikon high-speed locomotive (Reference No. 8) built for the **Great Indian Peninsula Railway** is illustrated in Fig. 327. Each axle is driven by a twin motor (rated at 750 h.p., 1400 volts); the inside form of the Oerlikon coupling drive, Fig. 307, with flexible gear wheel being employed. Fig. 328 shows the arrangement.

The body is of the box type. The whole of the auxiliary machinery and the starting rheostats are located in a central compartment above the three driving axles. Adjacent compartments contain the control gear, and end compartments form the driving cabs. Two side corridors connect the driving compartments and provide access to the machinery compartment, access to the control compartments being obtained from the driving compartments through doors suitably interlocked with the high-tension circuits.

The auxiliary machinery comprises duplicate compressors, rotary exhausters, and blower sets, and a special three-unit motor generator (operating in parallel with a battery) for supplying the train lighting and control circuits at constant voltage.

The control gear is of the individual contactor electro-pneumatic type, and is arranged for double series-parallel control with two shunted-field steps for each combination of the motors. A noteworthy feature is

the use of inductive shunts having the same "time constant" as the field windings.

The whole equipment is divided into two halves, and simple arrangements are made for the isolation of either half. Any defective motor may be isolated by moving the appropriate reverser (by hand) to the "off" or "cut-out" position. The main connections are shown in Fig. 177.

All the control and auxiliary (1500-volt) circuits are duplicated as far as possible, the two halves being separately protected, in each case, by fuses. Moreover, the supply to either or both halves of the main and auxiliary circuits may be obtained from either pantagraph.

Protection against short circuits in the high-tension wiring from the pantagraphs is provided by main fuses, and an electrolytic (aluminium cell) lightning arrester gives protection from lightning and surges.

The cooling air enters the motors at the commutator end, passes axially through the machines, and thence to the compartment containing the starting rheostats, from which it is ejected through louvres in the roof clerestory.

High-speed locomotive with tandem, frame-mounted motors. The tandem (end-to-end) arrangement of motors driving a common axle is due to the Swiss Locomotive and Machine Works, and its application to the Metropolitan-Vickers' passenger locomotives for the **Great Indian Peninsula Railway** is shown on Plate IV. This locomotive, Fig. 329 (Reference No. 9), has an "inside" frame, three driving axles, a guiding bogie, and a pony axle (which is carried in a special frame and is connected to the adjacent driving axle. The two axles adjacent to the bogie truck are not allowed end-play, but the axle adjacent to the pony axle is allowed an end-play of 2 $\times$ 1 in.

Each of the driving axles is driven through double-reduction single gearing from a pair of motors (each of which is rated at 360 h.p.), which are mounted in tandem on the locomotive frame above the driving wheels. The main gear wheel is fixed to a short quill and is arranged centrally between the driving wheels, the drive from quill to axle being effected by a universal coupling according to the method shown in Fig. 308. The coupling is a special type (which is a modification of the Oldham coupling) developed by the Swiss Locomotive Works. The Brown-Boveri linkwork coupling is also suitable for this drive, and, in fact, was employed on two axles of the trial locomotive.

The six motors are controlled on the double series-parallel system by electro-pneumatic contactors, and no provision is made for regenerative braking. The motors are ventilated by two blowers and air trunks; the (three) motors on one side of the locomotive being connected to one air trunk, and the motors on the other side being connected to another trunk.

The body is of the box type and is divided into five main compartments (viz. two driving cabs, a central compartment above the driving wheels enclosing the main motors, a high-tension compartment containing the control gear and rheostats, and a compartment containing the auxiliary machinery).

Views of the control compartment are shown in Fig. 329A. This compartment is located above the bogie truck and is divided into two portions by a central gangway, on each side of which are arranged the contactors

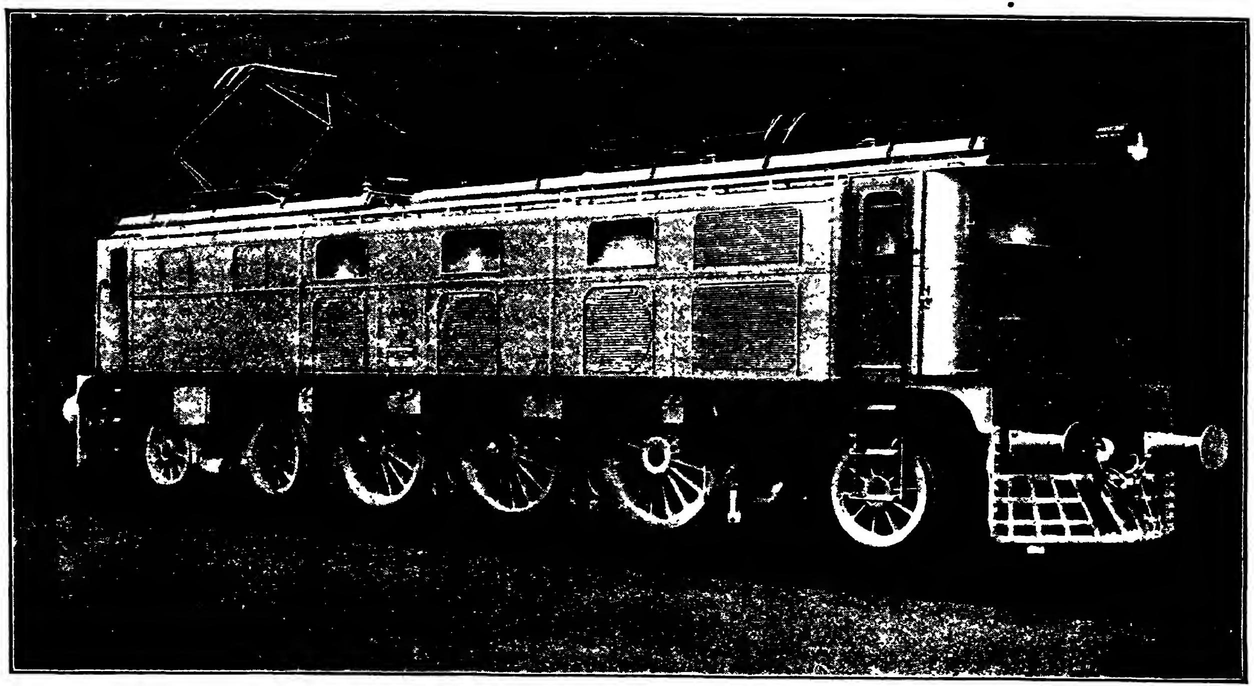


FIG. 329.—High-speed Locomotive (G I P. Railway) with Tandem Motors. (Metropolitan-Vickers.)

and rheostats. The contactors are mounted in compartments above the rheostats, and adequate provision is made for dissipating the heat produced by the latter. The reversers and cam-operated re-grouping switches are mounted in small compartments above the motors.

The auxiliary machinery is located in a compartment above the pony axle.

Gearless locomotives. The type of high-speed locomotive (developed by the General Electric Co., Schenectady) having bipolar motors with the armatures directly upon the axles is in service on the New York Central and the Chicago, Milwaukee, and St. Paul Railways. These locomotives have shown good running qualities at high speeds, which may be attributed to (1) the relatively small size of armature carried upon the driving axles, (2) the use of guiding bogies, and (3) the special features incorporated into the trucks to check transverse oscillations and to reduce the lateral pressure exerted by the wheel flanges on the rail head. Moreover, in the case of the New York Central locomotives, the maintenance costs have been exceptionally low.

Usually, two or more driving trucks are employed, and the hinge joints are designed to allow of no relative lateral movement between the trucks. The guiding bogies are connected to the main truck frames by centre-pin bearings, and their outer end-frames are fitted with inclined planes on which the outer ends of the main truck frames (to which the draw-gear is fitted) are supported by rollers ; this arrangement tending to retain the bogies in their central position relative to the main trucks. Hence any lateral motion of the main truck frames relative to the bogies causes the rollers to move up one or other of the inclined surfaces, thereby lifting the main truck frame and the cab, and bringing a large restoring force into action. The design of the inclined planes and rollers is such that there is no tendency to oscillate during the return movement following a displacement.

The motors are of the special bipolar type [described in Chapter IV (p. 76)] with vertical and almost flat pole faces (Fig. 36) to allow for the vertical movement of the armature in service. They are enclosed by sheet steel plates to protect them from track dust and dirt, and also to permit the efficient use of forced ventilation. A separate blower is employed for each motor, the several blowers on each truck being coupled together and driven by a single motor. The air is delivered at the commutator end, and circulates through and around the armature and field coils. It then passes to the rheostat compartments in the body of the locomotive, and finally leaves through louvres in the outer walls of these compartments.

Fig. 330 shows the general arrangement of the motor, blower, and rheostats in the **Chicago, Milwaukee, and St. Paul** locomotives. In this case the control apparatus is located in two compartments, with cylindrical roofs, which extend from the driver's cabs, the latter being arranged on either side of a central compartment containing the train heating equipment (viz. an oil-fired steam generator and accessories).

This locomotive (Reference No. 10) has 12 driving axles which are distributed over a wheel-base of 57 ft. 4 in., there being four trucks, each having a relatively short wheel-base. The two inner trucks each have four

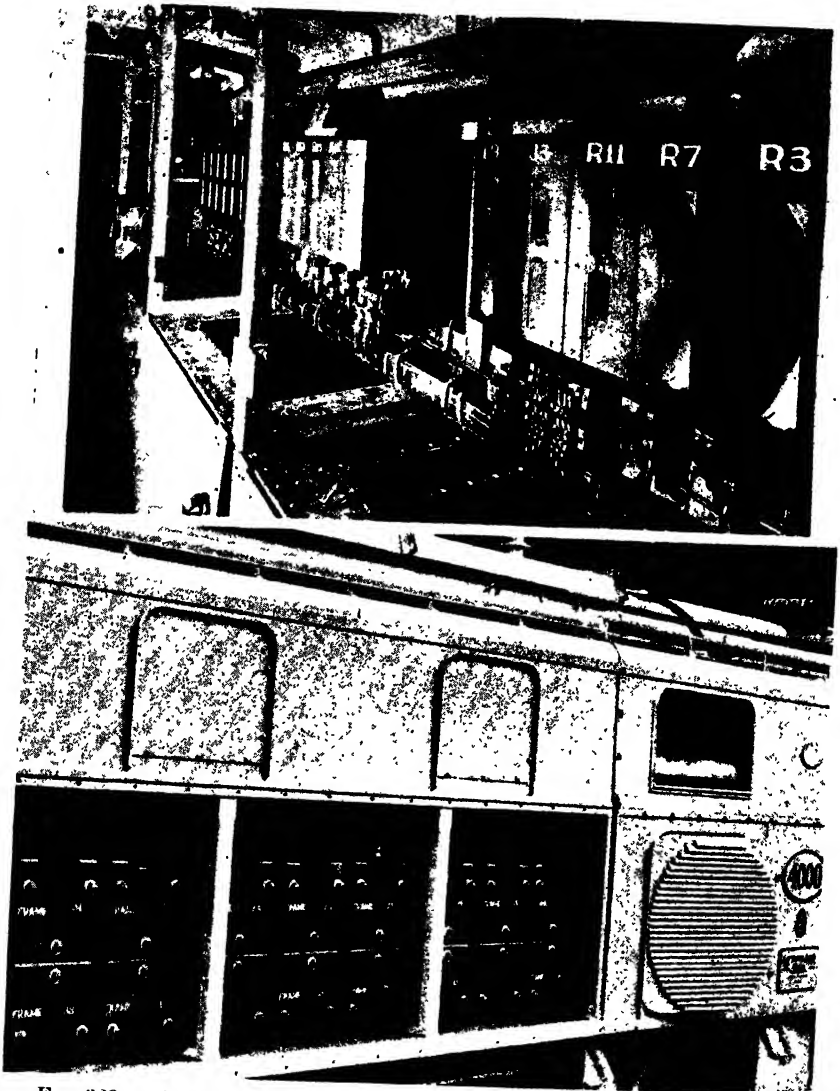
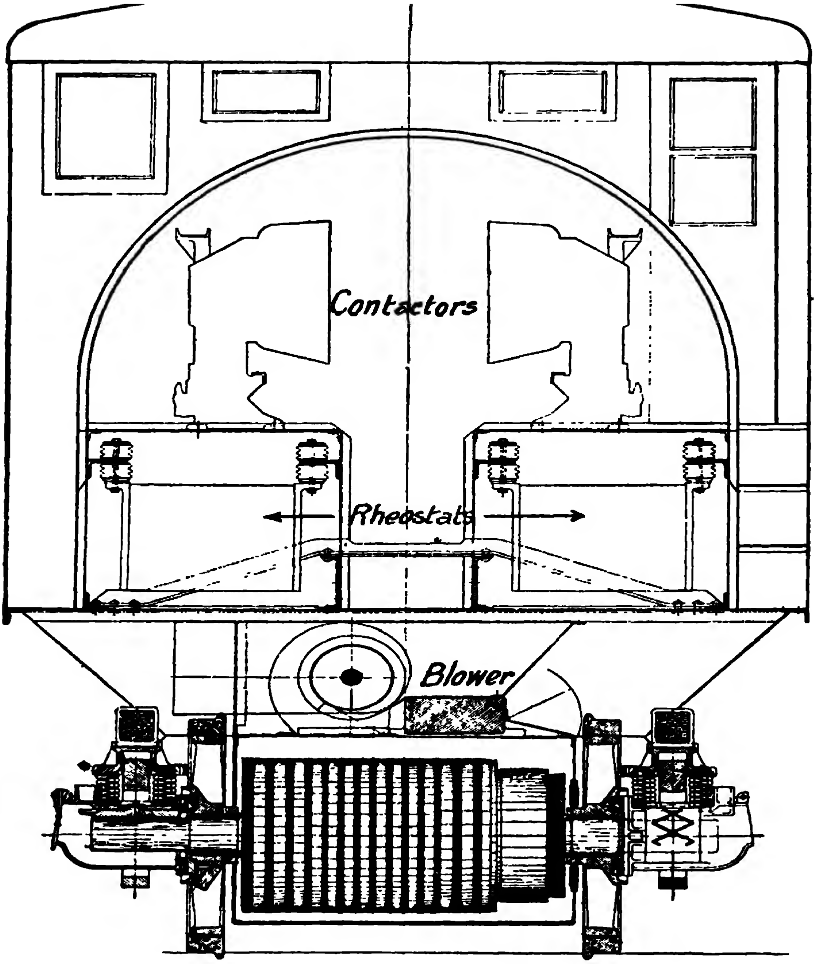


FIG. 329A.—Control Apparatus and Rheostat Compartments of Locomotive illustrated in Fig. 329.



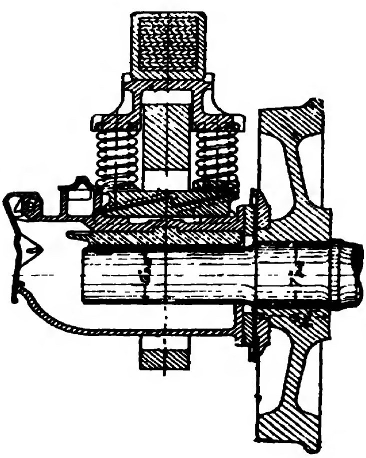


FIG. 330.—Transverse Section of High-speed Gearless Locomotive (C.M. and St. P. Railway) and Detail of Journal Box of Guiding Axle. (General Electric Co., Schenectady.)

FIG. 330A.—High-speed Gearless Locomotive. (General Electric Co., Schenectady.)

axles and a rigid wheel-base of 13 ft. 9 in. The outer trucks each consist of two driving axles (wheel-base, 4 ft. 7 in.) and a pony axle, the overall wheel-base being 67 ft. Each pony axle is allowed an end play of half an inch on each side of its central position, but such end-play is opposed by frictional resistances introduced by wedges in the journal boxes (Fig. 330). This feature, together with the inclined surfaces and rollers on the truck frames (mentioned above) effectively protects the track rails from lateral displacement. The dead weight per driving axle is about 9600 lb., of which about 5000 lb. is due to the armature and commutator.

A **New York Central** locomotive (Reference No. 11) is shown in Fig. 330A. In this case the guiding bogies are equipped with motors, there being a total of eight driving axles and four trucks. The motors of each truck are permanently connected in parallel, and the four pairs are controlled on the double series-parallel system. The body is supported by centre bearings and is divided into three compartments, viz. two driving cabs and a central compartment containing the control apparatus, compressor, and blower. The contactors are arranged back to back (about 6 ft. above the floor) along the centre of this compartment; the rheostats are mounted above, and the blower and compressor are fixed to the floor. Gangways are provided on each side for inspection purposes. The train steam-heating apparatus (consisting of an oil-fired boiler) is located in the driving cabs; the boiler being placed in one cab, and the water and oil tanks in the other.

Locomotives with collective connecting-rod drive. This type of locomotive is usually cheaper to construct than one having frame-mounted motors and individual-axle drive. It is suitable for large outputs at slow and moderate speeds (i.e. freight service), for which conditions its adoption is justified in cases where frame-mounted motors are necessary. Although in the past side-rod locomotives have been constructed for high-speed running, the present tendency is towards the use of the individual-axle drive for high-speed, direct-current, and single-phase locomotives.

An example of a direct-current locomotive with distributed collective drive and Metropolitan-Vickers' equipment is illustrated in Fig. 331, and details of construction are shown in Plate V. A number of these locomotives (Reference No. 12) are in service on the **Great Indian Peninsula Railway** for freight traffic. Each locomotive has two three-axle trucks with coupled driving wheels, the coupled wheels of each truck being driven by connecting rods from a jack-shaft which is twin-geared to a twin motor rated at 1300 h.p., 1500 volts. The drive is similar to that (Fig. 342) used, with success, in a number of single-phase locomotives.

The two trucks are connected together by the under-frame of the body (which transmits, via centre-pin bearings, the tractive effort from one truck to the other), and also by a special linkwork which is designed to prevent " nosing " and transverse oscillations of the trucks.

The driving motors are mounted on the truck framing between the outer and intermediate axles, and the jack-shafts are symmetrically placed with respect to these axles. Each motor has a built-on blower and is fitted with twin (helical) gearing with springs in the pinions (Fig. 31). Adjacent to the motors are mounted the reversers, together with the contactors and rheostats for tapped- and shunted-field control. This apparatus and the motors are enclosed by hoods which are separate

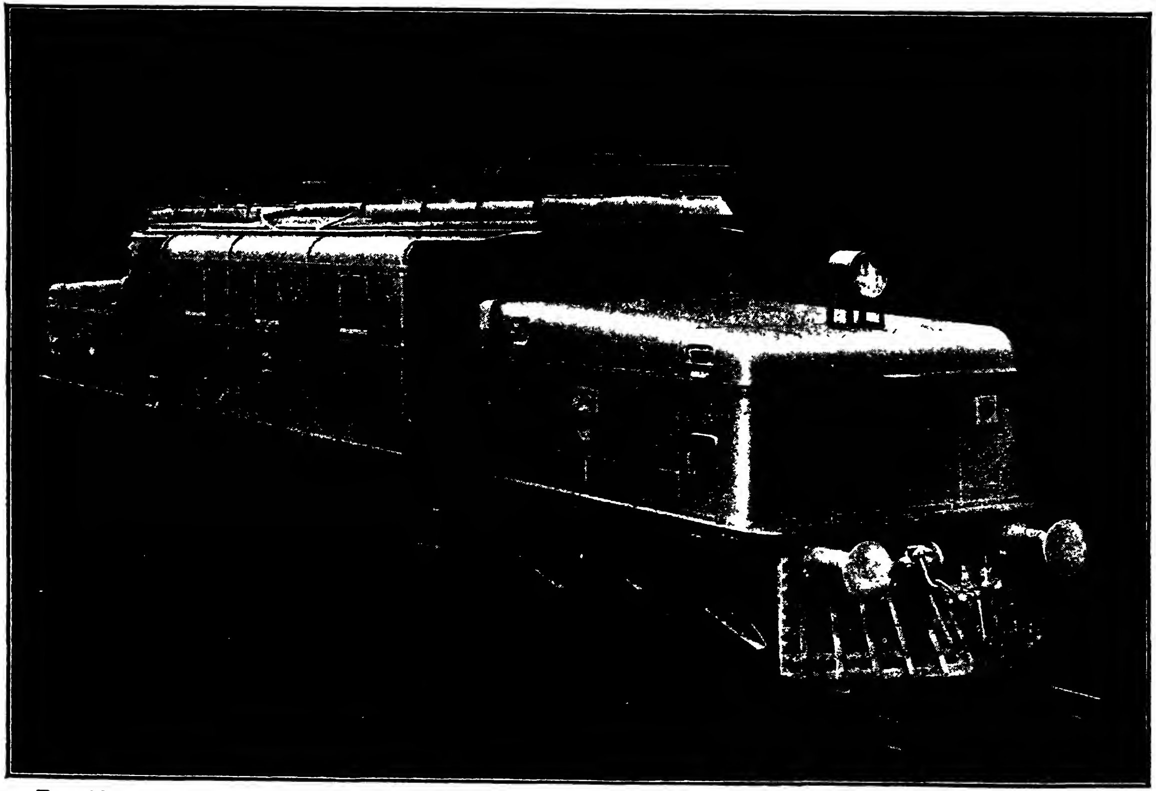


FIG. 331.—Freight Locomotive (G.I.P. Railway) with Distributed-collective Drive. (Metropolitan-Vickers.)

from the main body and can be completely removed, as shown in Fig. 332. Views of the driving cab are shown in Fig. 333. The master controller is arranged for regenerative braking, and is of the type illustrated in Fig. 156. The motor cut-out switch (control circuit) is adjacent to the master controller and is operated by the reversing handle of the latter.

The control apparatus (contactors, cam switches, etc.) is arranged in two compartments which are separated by two other compartments—occupying the centre of the body—containing the rheostats. Access to

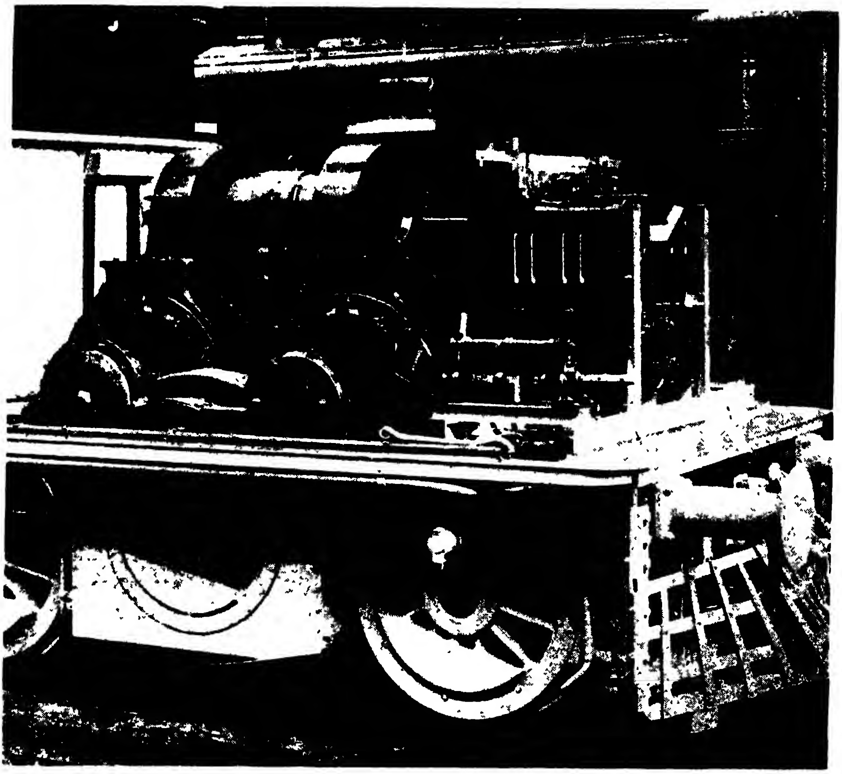


Fig. 332.—One of the Driving Units of Locomotive illustrated in Fig. 331.

these compartments is obtained from a side corridor communicating with the driving cabs. Each control compartment has a central gangway (transverse to the body), on either side of which the apparatus is arranged. The rheostat compartments have also a central gangway, the rheostats being arranged in tiers on each side. Views of the control and rheostat compartments are shown in Fig. 333A.

The auxiliary machinery is located in compartments adjoining the driving cabs, as shown in Plate V.

II. Single-phase Locomotives

Compared with the high-voltage, direct-current locomotives which we have been considering, a large single-phase locomotive is characterized

by its simplicity and the absence of isolated and locked compartments containing a multitude of apparatus and connections. This outstanding feature is due to (1) the absence of rheostats, (2) the low voltage of the motors, and (3) the simplicity of the control gear owing to the elimination of series-parallel control.

In general, the only high-tension gear in the *body* of a single-phase locomotive is the main oil switch and the current transformers for operating the protective relays and instruments.

The motors, or motor groups, are usually connected permanently in parallel and are supplied from a single transformer; a single tapping-switch or group of contactors being employed for controlling the voltage applied to the motors. In some cases, however, two transformers and groups of contactors are employed.

The auxiliary plant (e.g. compressors, blowers, lighting motor-generator set) is supplied at low voltage from a tapping on the main transformer.

Heavy freight locomotive with geared, axle-mounted motors. The general arrangement of a locomotive of this type (which is in service on the **German State Railways**) is shown in Fig. 334. The locomotive (Reference No. 13) is of the articulated-truck type with six driving axles, and has Siemens-Schuckert equipment, the motors being of the type shown in Fig. 55.

The six motors are connected in parallel and are supplied from two transformers, each of which has its own group of contactors and a triple (three-legged) choking coil, arranged in accordance with the scheme of Fig. 186. The centre points of each of the triple choking coils are, however, connected to a third choking (or equalizing) coil, and the motors are connected to the centre-point of this coil. The transformers, therefore, operate in parallel. This arrangement with duplicate transformers was adopted in preference to that with a single transformer in order to obtain a better distribution of weight on the locomotive.

The body is constructed in two halves, each half being fixed to the corresponding truck. The two halves are close coupled and are provided with a short communicating gangway. The driving cabins occupy the central portions of each half-body, and adjoin compartments (which are connected by a gangway) containing the auxiliary machinery (viz. two blower sets and an air compressor). Narrow, tapered extensions of the body beyond the driving cabins contain the transformers, main oil switch, choking coils, and air reservoirs. The contactors are located in hoods adjacent to the transformer compartments.

Locomotives with individual-axle quill drives and frame-mounted motors. Locomotives of this type have been in operation on the **New York, New Haven, and Hartford Railroad** since the inauguration of the electric services in 1906. Both gearless and geared types are now in operation, the former (which was the original type of locomotive) being employed for high-speed passenger service, and the latter for passenger and freight service. All locomotives have a spring drive from quill to driving wheels, the latest form of which is shown in Fig. 305. In all cases the designs and equipment are due to the Westinghouse Co. Certain of the locomotives have to operate dually with alternating current (at

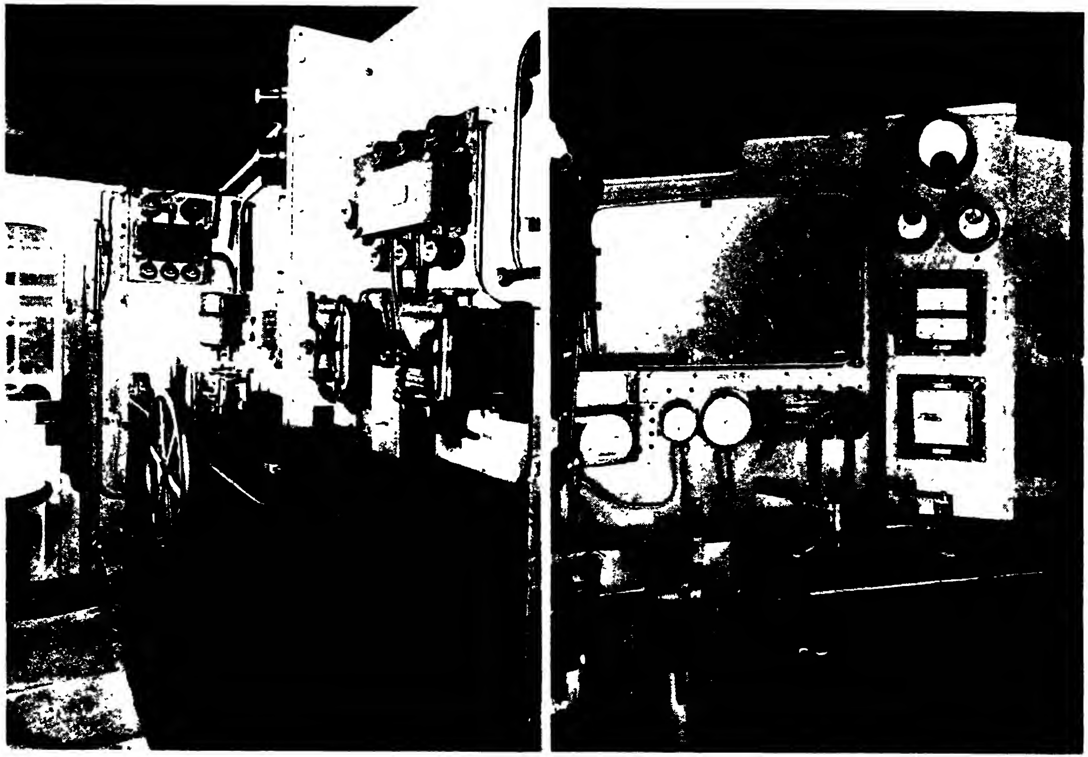


FIG. 333.—Driving Cab of Locomotive illustrated in Fig. 331. In the foreground of the left-hand illustration are the Auxiliary Control Switches and the Control-circuit Motor Cut-out Switch. The right-hand illustration shows the Master Controller.

FIG. 333A.—Control Apparatus and Rheostat Compartments of Locomotive illustrated in Fig. 331. (The left-hand View shows the "Bomb" Fuses for the High-voltage Auxiliary Circuits.)

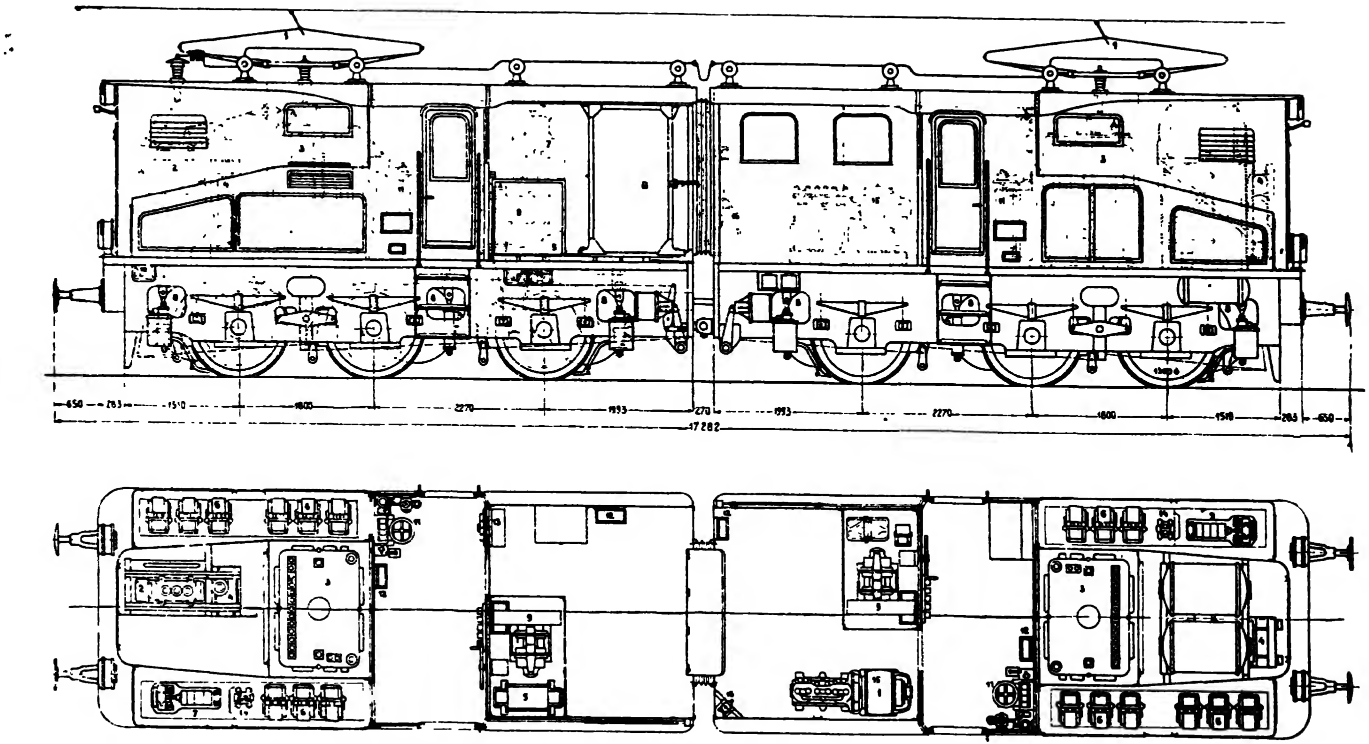


FIG. 334.—General Arrangement of Single-phase Freight Locomotive (German State Railways) with Axle-mounted Motors. (Siemens-Schuckert.)

11,000 volts, 25 cycles) and direct current (at 650 volts),* and these have the motors and control gear specially arranged for this purpose, according to the scheme described on p. 290.

A typical locomotive is illustrated in Fig. 335, which shows the box form of body adopted for all freight and passenger locomotives.† This locomotive (Fig. 335, Reference No. 14) is in freight service and is equipped with twin motors, a typical twin motor being shown in Fig. 336. Each element of the twin motor is of the Westinghouse series type (p. 101) and has a one-hour rating of about 200 h.p. at 275 volts, 25 cycles. Such twin-motor equipments have been standardized since 1912 for all freight and

FIG. 335. -Westinghouse Single-phase Locomotive.

passenger locomotives. The trucks are of the equalized articulated type with radial pony axles, and are shown in Fig. 337. This illustration refers to the trucks of an experimental locomotive equipped with frame-mounted geared single motors. Service tests on this locomotive, and a similar locomotive equipped with twin-motors, demonstrated that twin-motor equipment possessed the advantages of lighter weight and a greater ease of maintenance.

The body, in addition to being fitted with centre bearings, is spring supported on eight friction plates (*A*, Fig. 337), the springs being contained in spring pockets attached to the underside of the body. Spring plungers are also fitted to the underframe to engage the side bearings, *B*, above the pony wheels, their function being to check transverse oscillations of the body.

The special features of the trucks and the twin-motor equipment have been retained with modifications in larger locomotives recently built for

* The New Haven trains run into New York City over the New York Central lines, which are electrified on the direct-current system.

† The "steeple" type of cab is adopted for shunting locomotives (see Fig. 442).

passenger service. In these locomotives (Reference No. 15) each truck has three driving axles, and a radial pony axle is fitted at *each* end. Each truck frame, instead of being built-up as in the example shown in Fig. 337, is a single steel casting, and weighs about 18,000 lb. This one-piece form of construction avoids the large amount of machining and fitting which is necessary with a built-up frame.

The control gear is of the electro-pneumatic, unit-switch type, and is arranged for dual operation, according to the scheme shown in Fig. 206. The control circuits are supplied from duplicate 32-volt storage batteries.

The transformer (rated at 2100 kVA.) is of the air-blast type, and is used solely for supplying the motors and auxiliary circuits, the train heating being by steam supplied by an oil-fired flash boiler carried on the locomotive.

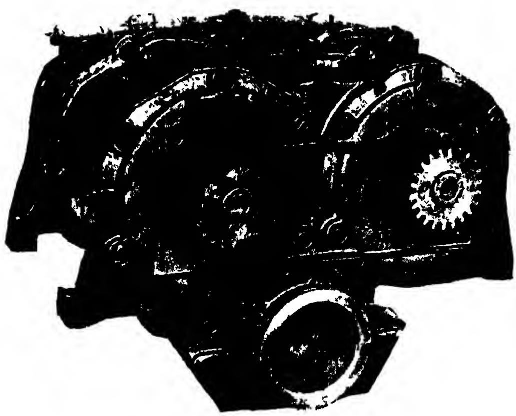


FIG. 336.—Westinghouse Twin Motors for Single-phase Locomotives.

High-speed locomotives with individual-axle drive and frame-mounted geared motors. The principal single-phase locomotives of this type are of the Brown-Boveri design with outside link-work drive, as shown in Fig. 302 and described on p. 423. Such locomotives have been standardized by the Swiss Federal Railways for express passenger services, and details of a typical locomotive are shown in Plate VI.

This locomotive (Reference No. 16) has four driving axles, a guiding bogie, and a trailing pony axle, combined with the adjacent driving axle so as to be equivalent to a bogie truck. The general design and arrangement of the locomotive frame is similar to that of the direct-current Paris-Orléans locomotive (p. 452), except for the unsymmetrical wheel arrangement, but, in the present case, the transmission gear is fitted only at one end of each axle (instead of both ends as in the previous case (Fig. 338) which have three driving axles). The body is of similar shape to that adopted for lighter passenger locomotives.

The four driving motors (Fig. 68) are each rated at 775 h.p. They are connected in parallel and supplied from a single transformer having seven tappings on the secondary winding, the control of the voltage being effected by a motor-driven tapping switch (Fig. 196).

The transformer is of the oil-cooled type with forced oil circulation (by pump) and a separate oil cooler, which consists of a nest of drawn steel tubes located beneath the running board on the side of the locomotive remote from the driving side. This form of cooler (Fig. 339) has given very satisfactory results in service and possesses the advantages that it is external to the locomotive body, requires no blower or fan, and reduces the amount of auxiliary equipment.

The motors are forced ventilated by separate blowers, which are driven in pairs; as shown in Fig. 339. The shaft of one blower is extended for coupling to a 36-volt direct-current generator (for supplying the control circuits) and a centrifugal pump for circulating the cooling oil of the transformer.

The supply to the auxiliary circuits (viz. the motors driving the blowers and compressors, and the heaters in the driving cabs) is controlled by a two-way switch by means of which this supply may be obtained either from the 220 volt tapping on the main transformer or an external supply plugged into a receptacle on the side of the locomotive. The auxiliary machines and circuits may, therefore, be tested in the depots without exciting the main transformer.

FIG. 337.—Trucks of Westinghouse Single-phase Locomotive.

The reversers are mounted on the frames of the motors and are coupled together for operation by the usual electro-pneumatic mechanism. Any reverser, however, may be uncoupled and locked in the "off" position for the purpose of cutting-out a defective motor.

A gangway is provided at the commutator end of the motors to facilitate inspection of the brush-gear, etc. No gangway is provided at the opposite (blower) end, but the side wall is removable, as shown in Fig. 339.

Locomotives with collective and distributed-collective drives. Fig. 340 shows the general arrangement of a Brown-Boveri **shunting locomotive** with collective drive, which is in service on the **Swiss Federal Railways.** This locomotive (Reference No. 17) has a single motor (700 h.p.) which is geared to a jack-shaft, from which the coupled wheels are driven by connecting rods. To obtain a symmetrical drive, gearing (of the single helical type) is fitted at each end of the armature shaft, and

the pinions are fitted with both springs and slipping couplings to relieve the armatures from the impacts inseparable from shunting service. The armature winding is provided with resistance connections which are arranged as shown in Fig. 66.

The motor, together with the reverser, blower, and motor-generator set (for supplying the control and lighting circuits), are located at one end of the locomotive, and the transformer (with the built-on tapping

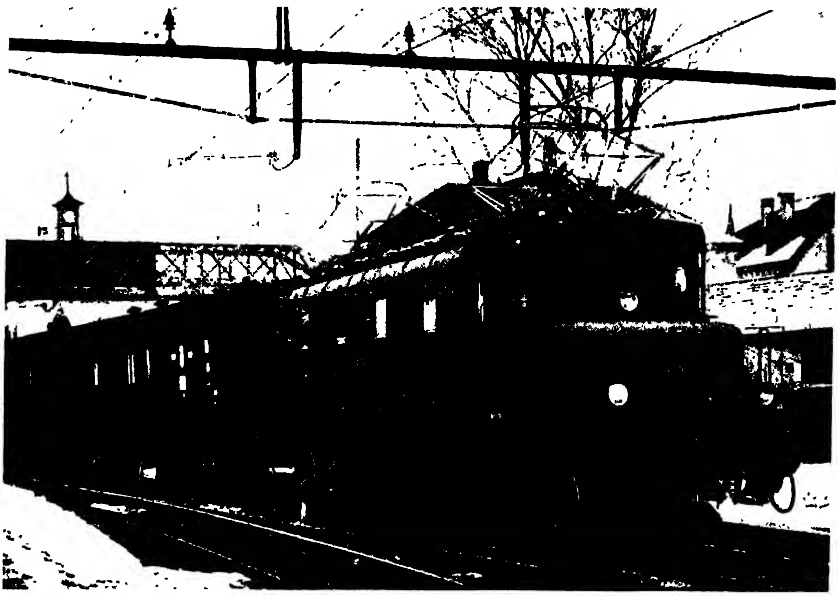


FIG. 338. —Passenger Locomotive (Swiss Federal Railways) with Brown-Boveri Individual-axle Drive.

switch), together with the main oil switch and the air compressor, are located at the other end.

The cab is of the "steeple" type and contains only the master controller, control switches, and brake levers. All controls, as well as the brake levers, are duplicated and mechanically coupled, so that the driver may commence a switching operation at one end of the cab, and, if necessary, complete it at the other end.

The general arrangement of a **passenger locomotive** with collective drive is shown in Fig. 341, and is representative of the locomotives in service on the **Swedish State Railways** for passenger and freight traffic.*

The locomotive (Reference No. 18) is built with a plate frame, and has three driving axles and two pony axles (Bissel trucks). Two pairs of driving wheels are driven by horizontal connecting rods from a jack-shaft, and the remaining pair of wheels is coupled to the adjacent pair by coupling rods. The jack-shaft has a diameter of 275 mm. (10·8 in.) at the journals, and is driven through twin gearing (of the helical type) from a twin motor, each element of which has a one-hour rating of

* The freight locomotives have a higher gear ratio than the passenger locomotives.

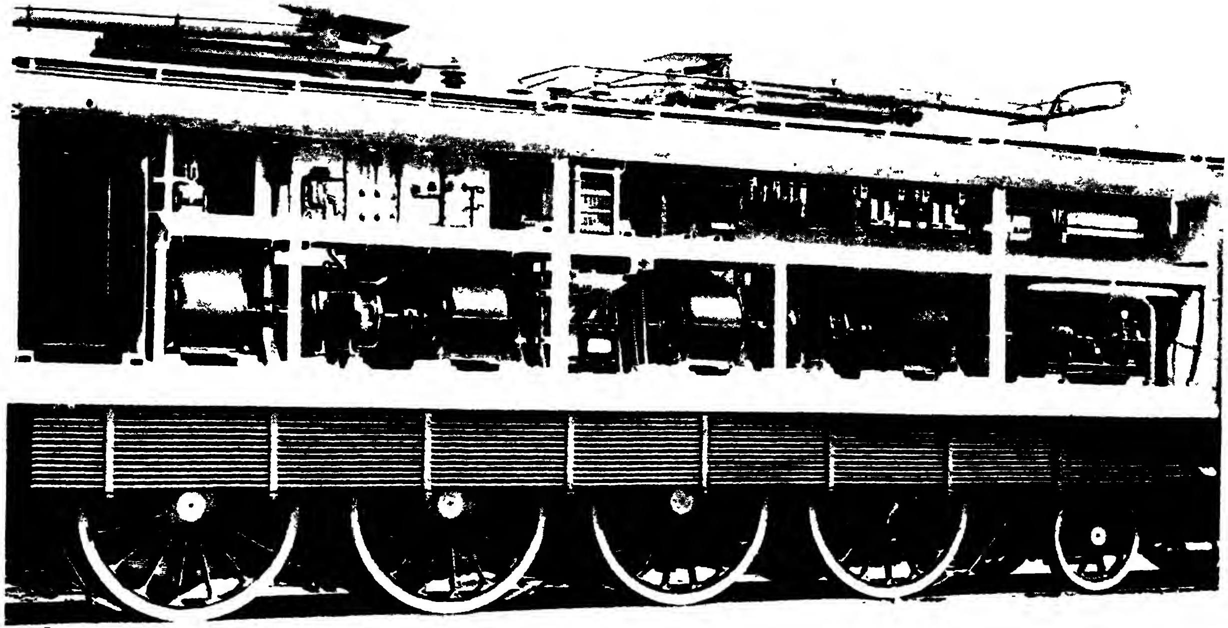


Fig. 339.—Brown-Boveri Locomotive (Swiss Federal Railways) with Individual-axle Drive. View, from Non-driving side, with side wall removed showing Blowers, Oil Pump, and Oil Cooler. Note.—This locomotive is equipped with bow, instead of pantagraph, collectors. A balancing vane is fitted to each collector to balance the wind pressure on the framework of the bow.

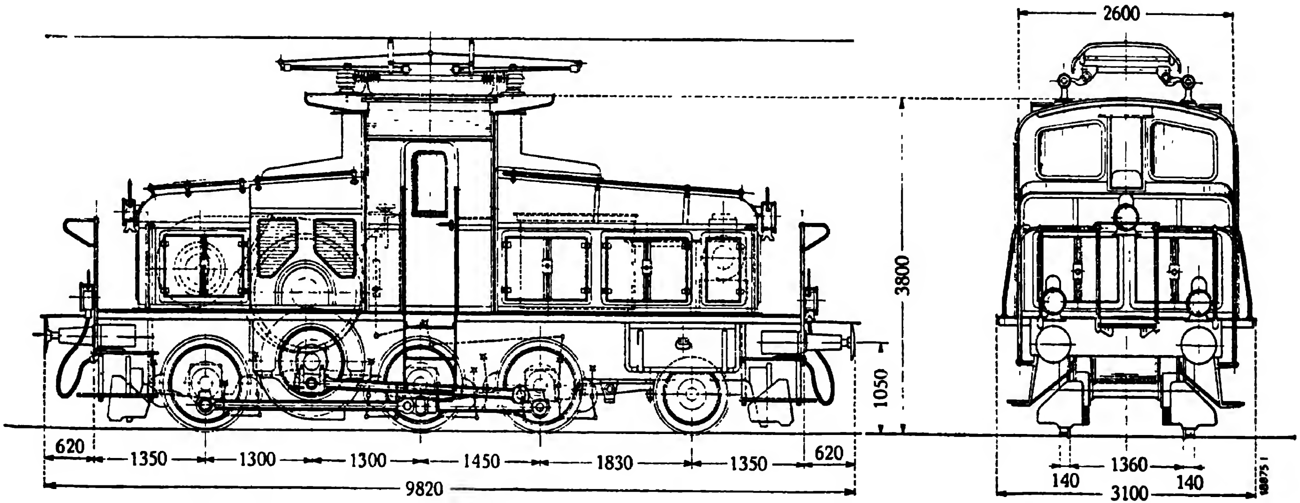


FIG. 340.—Shunting Locomotive (Swiss Federal Railways) with Collective Drive. (Brown-Boveri.)

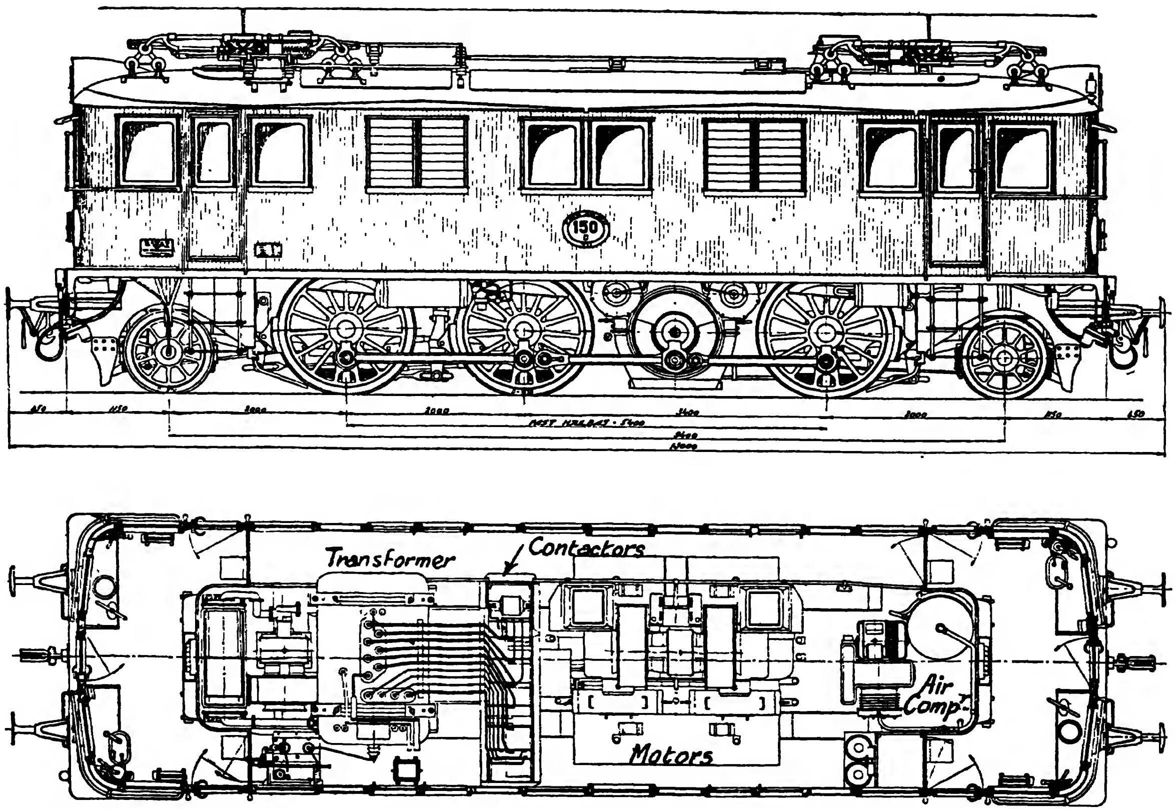


FIG. 341.—Freight and Passenger Locomotive (Swedish State Railways) with Collective Drive. (A.S.E.A.)

830 h.p., 390 volts, 730 r.p.m. Details of these machines are given on p. 107. The two machines forming a twin motor are permanently connected in series, and are ventilated by two blowers built on to the common housing in which the stators and bearings are mounted. The armature bearings have forced oil lubrication, which form of lubrication is also employed for the spring couplings between the armature shafts and the pinions, and for the jack-shaft bearings.

The main transformer has a continuous rating of 1490 kVA., of which 260 kVA. are required for train heating in winter. It is of the oil-cooled type with forced oil circulation, the oil being cooled in a separate cooler (which is of the multi-tubular type with air, supplied by a blower, as the cooling medium).

The secondary winding has tappings to give the following voltages: 168, 216, 264, 383, 528, 672, 840; all of which, except the 216-volt tapping (which supplies the control and auxiliary circuits), are used for controlling the main motors. The three highest tappings are also used for supplying the heating circuits through a suitable control switch.

The control gear is of the electro-magnetic contactor type, the contactors and reverser operating with single-phase current.

The whole of this gear is assembled on a frame of structural steel, which is located adjacent to the transformer, and the main connections are made with heavy copper bars.

The eighteen contactors are arranged in six groups, and the contactors of each group are connected to a tapping on the transformer and to two choking coils according to the scheme of Fig. 185, so that sixteen running points are obtained.

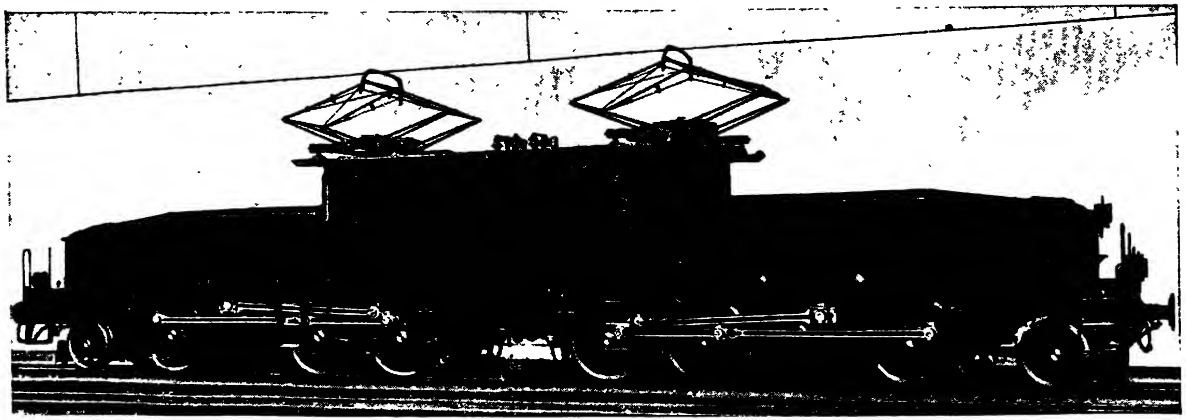
The lighting of the locomotive is normally obtained from a small auxiliary transformer, a low voltage (24 volts) being adopted on account of the low frequency. A battery of accumulators forms a reserve supply in the event of the traction supply failing, the change-over being effected automatically.

An example of a **heavy freight locomotive** with distributed collective drive is shown in Fig. 342, and details are shown in Plate VII. This locomotive (Reference No. 19) represents the latest type of freight locomotive adopted by the **Swiss Federal Railways.** It has Oerlikon electrical equipment and is arranged for regenerative braking. The two articulated trucks each have three coupled driving axles and a pony axle. Each truck is equipped with a pair of 625 h.p. motors, which are mounted together as a twin motor and drive the jack-shaft through single-helical gearing, spring pinions being fitted at each end of the armature shafts. Fig. 343 shows in outline the arrangement.

The body of the locomotive is constructed as a single unit and contains the main transformer, main oil switch, contactors, master controllers, and protective gear. It is carried on centre and side bearings in the usual manner, and can be removed completely.

The transformer is of the oil-cooled type with forced oil circulation, the oil being cooled in a separate cooler, which is supplied with cooling air by a blower. The motor driving this blower is coupled to the oil pump and also to a generator for supplying the control and locomotive-lighting circuits.

The transformer has double secondary windings, each with nine



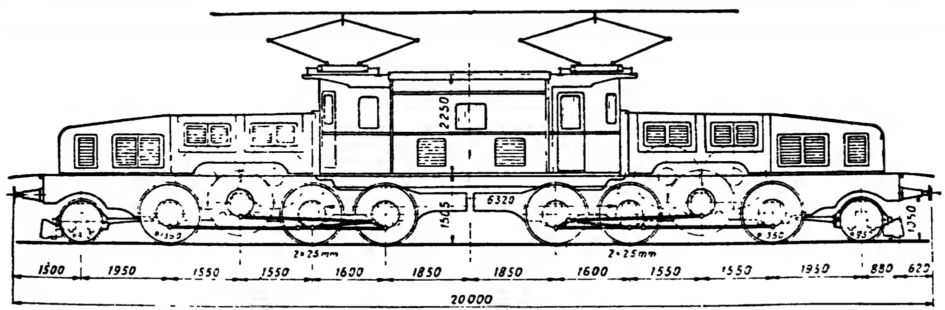


FIG. 342, 343.—Heavy Freight Locomotive, Swiss Federal Railways (Oerlikon.)

tappings. Each secondary winding is connected to a group of cam-operated contactors from which the motors are supplied in accordance with the scheme of Fig. 187A. The primary winding has tappings at 1000, 800, and 220 volts ; the 1000 and 800 volt tappings being for train heating, and the 220 volt tapping for the auxiliary circuits. Provision is

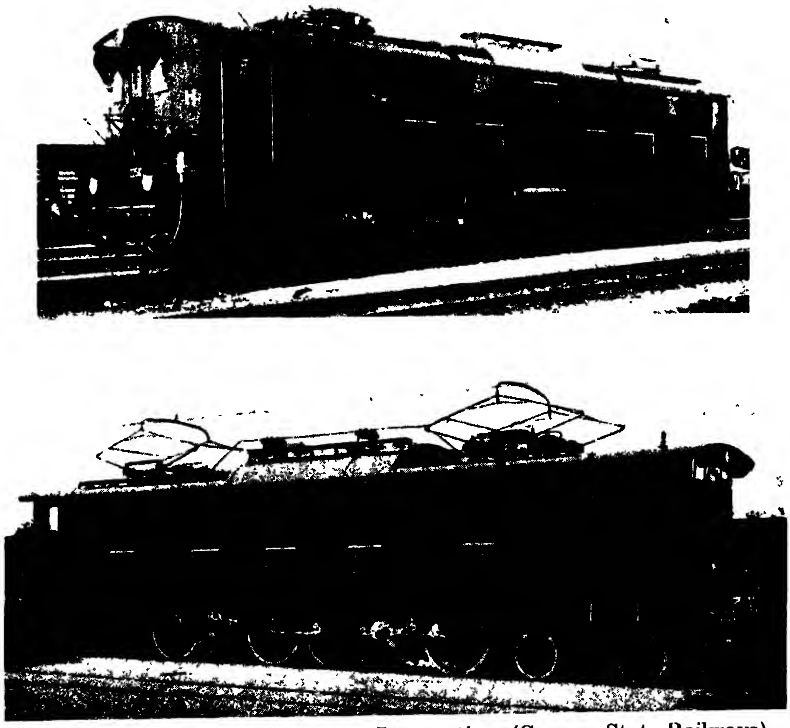


FIG. 344.—Freight and Passenger Locomotives (German State Railways) with Distributed Collective Drives. (Siemens-Schuckert.)

made, when the locomotive is in a depot, for supplying the auxiliary circuits without exciting the transformer.

Examples of recent Siemens-Schuckert **freight and passenger locomotives with distributed collective drive,** which are in service on the **German State Railways,** are illustrated in Fig. 344. One locomotive is designed for heavy freight service and the other for passenger service.

The **freight locomotive** (Reference No. 20) is of the articulated-truck type, each truck having three driving axles with coupled driving wheels driven from a jack-shaft by long connecting rods almost horizontal ; the drive being practically identical to that of the locomotive illustrated in Fig. 342. Each jack-shaft is driven through twin gearing by a twin

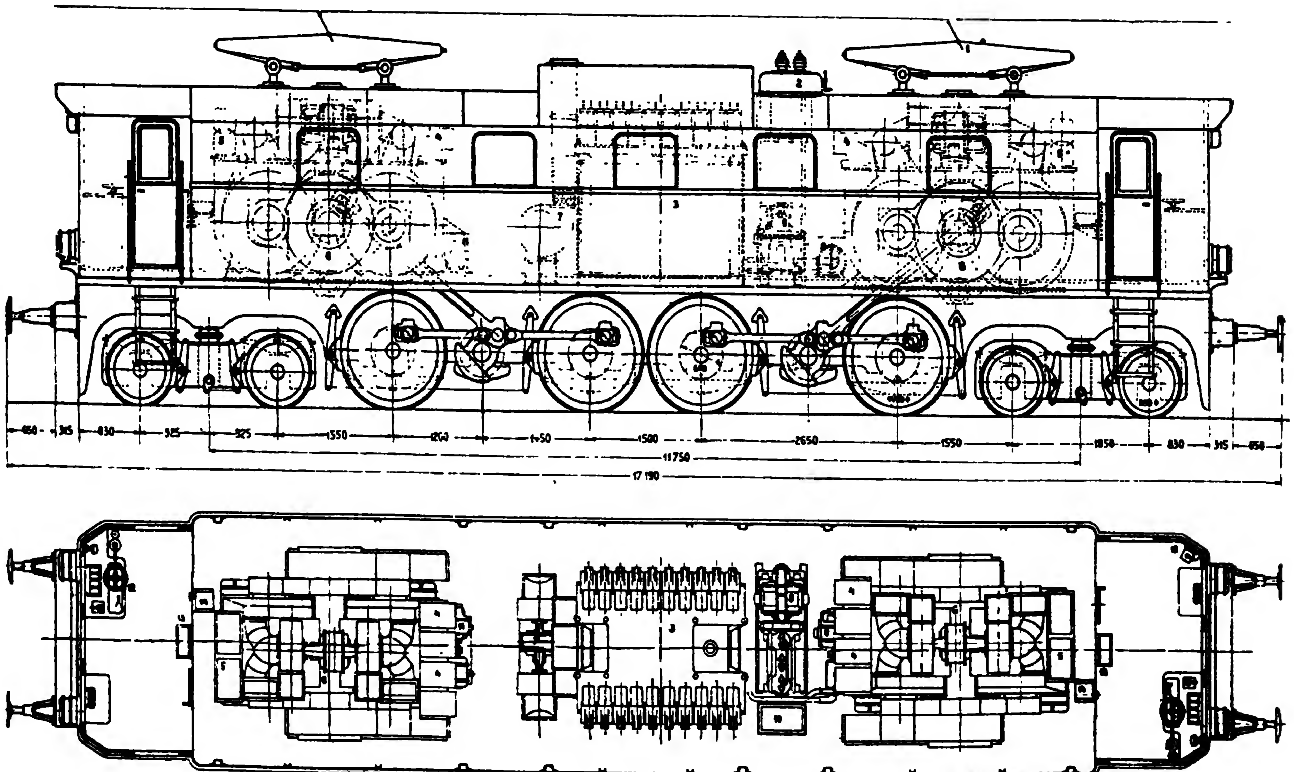


FIG. 345.—General Arrangement of Passenger Locomotive (German State Railways) with Distributed Collective Drive. (Siemens-Schuckert.)

motor of 2 × 490 h.p. The machines forming a twin motor are built with a common housing, which also carries the jack-shaft bearings, the blowers, the reverser, and the shunting resistances for the commutating-pole windings. The arrangement is similar to that adopted for the passenger locomotive.

The body of the locomotive is of the box type and is constructed in three sections; each end section being fixed to its appropriate truck, and

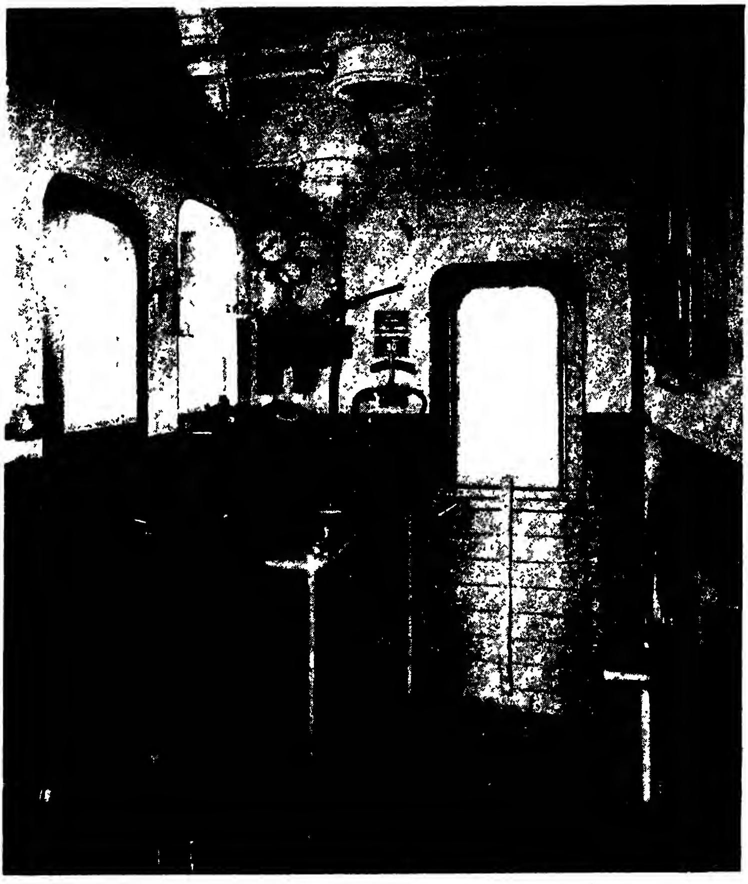


FIG. 346.—Driving Cab of Single-phase Locomotive. (Siemens-Schuckert.)

the central section being connected to each truck by pins. All the sections are of approximately the same width and height, and are flexibly connected so as to provide through communication from one end to the other. The layout of the interior of the body and the system of control are practically identical with those of the passenger locomotive.

The **passenger locomotive** (Reference No. 21) has a plate frame with four driving axles and two guiding bogies. The driving wheels are coupled in pairs to two jack-shafts, each of which is driven by connecting rods

from an intermediate shaft geared to a twin motor. The general arrangement is shown in Fig. 345. The intermediate shaft is on a level with the armature shafts, and occupies a central position between them. It is mounted in bearings in the housing which contains the stators (which are built separately, similar to Fig. 57) and armature bearings. The upper half of this housing is fitted with the blowers; and the reverser and shunting resistances for the commutating-pole windings are also mounted thereon. The complete assembly, together with a partially-assembled twin motor, can be seen in Fig. 315.

The body is of the box type and is constructed as a single unit. A driving compartment, Fig. 346, is provided at each end, and the remainder forms one large compartment for the motors, transformer, and auxiliary machines.

The transformer is of the oil-cooled type with forced oil circulation and an external oil cooler. It has double secondary windings, the tappings of which are connected to two groups of electro-magnetic contactors, according to the scheme of Fig. 186. The contactors are mounted on the top of the transformer, as shown in Fig. 315.

III. Three-Phase Locomotives

Three-phase locomotives for operating on low-frequency, medium-voltage systems are characterized by their extreme simplicity, owing to the absence of transformers and tap-changing gear. A large number (over 400) of these locomotives are in service on the **Italian State Railways,** the majority being equipped with two large (1000 to 1300 h.p.) gearless induction motors and scotch yokes. Typical freight and passenger locomotives are illustrated in Fig. 347.

The **freight locomotive** (Reference No. 22) is equipped with two 1000 h.p. motors, which are controlled on the cascade-parallel system, the synchronous speeds—corresponding to normal frequency ($16\frac{2}{3}$ cycles)—being 14 ml.p.h. and 28 ml.p.h. A large number of these locomotives are in service on the Giovi-Genoa lines, on which the gradients are long and heavy, the maximum gradient being 3·5 per cent. The total weight of the locomotive is 60 tons, all of which is on the driving wheels. Two locomotives (one hauling and the other pushing) are capable of handling freight trains weighing 260 tons (excluding the locomotives) over the Giovi lines at a speed of 24·3 ml.p.h. up the gradients. On the return journey (down the gradients) two locomotives are coupled together at the front of the train, and the gradients are descended at a speed of about 30 ml.p.h. with the motors acting as induction (asynchronous) generators, from 500 to 700 kW. being returned to the supply system by each locomotive. The performance of these freight locomotives has been highly satisfactory, and their adoption on the Giovi lines has enabled the capacity of these lines under steam conditions to be nearly trebled, this increase in capacity being due to the higher speeds and the heavier trains.*

In the latest locomotives the Bianchi jointed-linkwork drive, Fig. 310, is employed instead of the Scotch-yoke drive.

* For interesting data relating to the Giovi lines and the performance of the electric locomotives, see *The Engineer*, vol. 117, pp. 89, 115, 143, 194, and *The Electric Journal*, vol. 11, p. 550.

The **passenger locomotive** (Reference No. 23) is equipped with two 1300 h.p. two-speed induction motors, which are controlled on the changeable-pole cascade-parallel system, so that four running speeds are

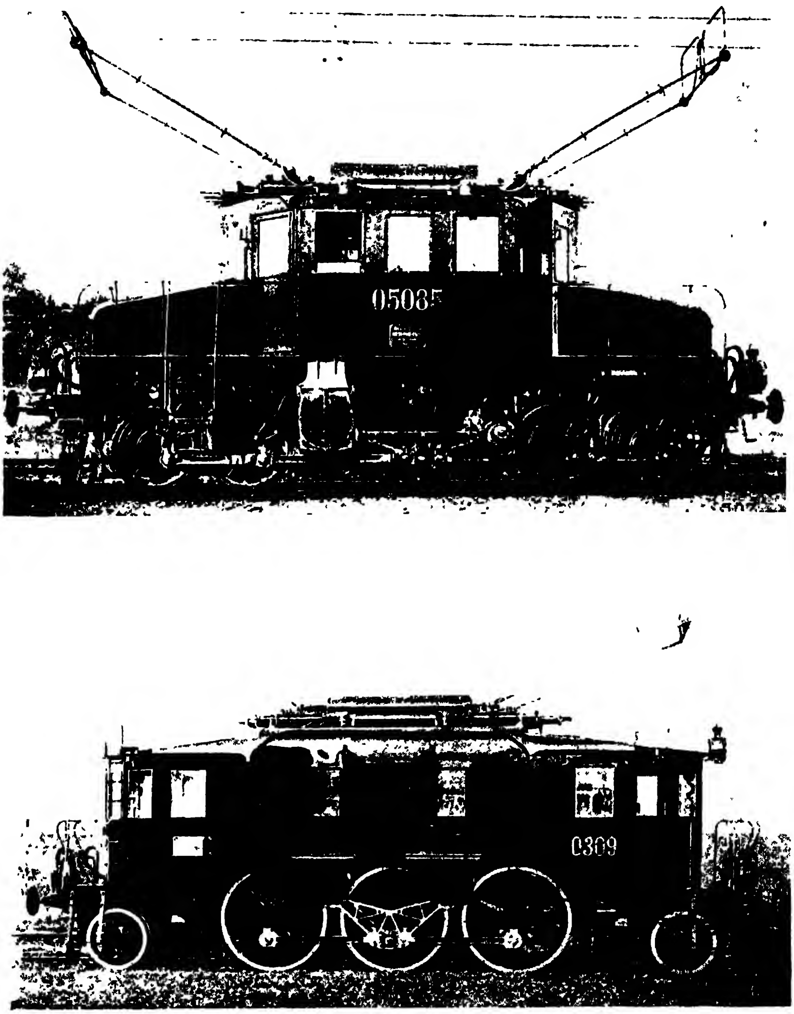


Fig. 347.—Three-phase Freight and Passenger Locomotives (Italian State Railways) with " Scotch Yoke " Drive. (Società Italiana Westinghouse.)

obtained, these speeds (corresponding to the synchronous speeds at normal frequency, $16\frac{2}{3}$ cycles) being 23·3, 31, 46·6, 62 ml.p.h. The weight of the complete locomotive is 71 tons, of which from 50 to 44 tons is adhesive weight. The variation of the adhesive weight is obtained by transferring weight from the driving axles to the pony axles.

The shafts of the motors are supported in bearings carried in special

supports from the locomotive frame,* and the concentricity of the stator and rotor is obtained by bearings located in the frame-heads of the motor (see Fig. 85, p. 140).

The tractive effort of the locomotive—corresponding to the rated load of the motors—at the four running speeds is as follows—

Connection of Motors	Synchronous Speed (ml.p.h.)	Tractive Effort (lb.)
8-pole, cascade	23·3	19,800
6-pole, cascade	31	19,800
8-pole, parallel	46·6	20,900
6-pole, parallel	62	13,200

Locomotives for operating on circuits of **normal frequency** (40 to 50 cycles per second)—for which a high line voltage (e.g. 10,000 volts) is necessary to avoid a high voltage drop due to the increased reactance of the trolley wires and rails—require to be equipped with transformers in order to obtain a suitable voltage (e.g. 1000 volts) for the motors, which in this case are relatively high-speed machines and transmit their power through gearing.

A **passenger locomotive** in service on the 45-cycle, 10,000-volt lines of the Italian State Railways is illustrated in Fig. 348. The locomotive has four driving axles and two pony axles, and weighs 90 tons, of which about 64 tons is adhesive weight. It is equipped with two 1300 h.p., 930-volt, forced ventilated, changeable-pole motors, which are twin-geared to jack shafts (gear ratio 2·7), from which the coupled driving wheels are driven by Scotch yokes. The motors have pole-changing windings to give either six or eight poles (according to the schemes of Figs. 77 and 80), and are controlled on the cascade-pole-changing system (p. 296), an automatic liquid rheostat being employed for controlling the torque during starting.

The speeds and tractive efforts of the locomotive, corresponding to the one-hour ratings of the four combinations of the motors, are—

Connection of Motors	Synchronous Speed (ml.p.h.)	Tractive Effort (lb.)
8-pole, cascade	23·3	14,500
6-pole, cascade	31	14,500
8-pole, parallel	46·6	18,700
6-pole, parallel	62	15,400

The oil-immersed transformer is rated at 1730 kVA., and has primary (10,000 volts), secondary (930 volts), and tertiary (110 volts) windings; the tertiary winding supplying the auxiliary circuits. Efficient cooling is ensured by forced circulation of the oil through a series of exposed tubes located along one of the running boards, the arrangement being similar

* See *The Engineer*, vol. 116, p. 216, for details of these supports.

to that employed on the passenger locomotives (Fig. 339) of the Swiss Federal Railways.

The **freight locomotives** in service on these (45-cycle, 10,000-volt) lines weigh 75 tons, and have mechanical details practically identical with those of the low-frequency freight locomotives (Fig. 347), except that the motors are twin-geared to the Scotch yokes (gear ratio 3·625). The motors are wound for six poles and are controlled on the cascade-parallel system.

The synchronous speeds of the locomotive are 15·5 and 31 ml.p.h., and the corresponding one-hour tractive efforts are 22,000 lb. and 26,400 lb.

IV. Split-phase and Composite (A.C.–D.C.) Locomotives

Split-phase locomotives. A "split-phase" locomotive operates from a single-phase supply system and has driving motors of the three-phase

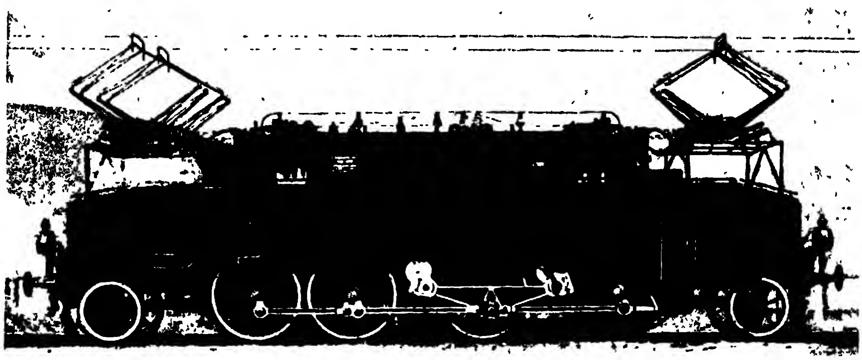


Fig. 348.—Three-phase Passenger Locomotive (Italian State Railways) with Pantagraph Collectors for 10,000-volt Supply. (Brown-Boveri.)

induction type. The motors are supplied with current, at the supply frequency, from a phase converter and are controlled in the manner explained on p. 301. As the functions of the phase converter are reversible, regenerative braking can be obtained in the same manner as with a three-phase locomotive.

Locomotives of this type have been developed by the Westinghouse Co. for coal traffic on the heavy grades of the Norfolk and Western and the Virginian Railways, U.S.A.; the distribution voltage being 11,000, and the frequency 25 cycles per second.*

The **Norfolk and Western** locomotives have distributed collective drives, and are operated as "double" locomotives, two locomotive "units" being permanently coupled together. A typical locomotive (Reference

* A split-phase locomotive designed (by Ganz & Co., Budapest) for operating from circuits of normal frequency (42 to 50 cycles per second) was in 1923 placed in service on a section of the Hungarian State Railways. In this locomotive control of the motors is effected by variation of voltage. Details of the system (due to de Kando) are given in the *Transactions of First World Power Conference* (London), 1924, vol. iv, p. 983.

No. 24) is shown in Fig. 349. The body of each unit is of the box type and is mounted upon two articulated trucks, each of which has two driving

Fig. 349 —Split-phase Locomotive in Heavy Freight Service on Norfolk and Western Railway (Westinghouse Co)

axles and one pony axle. The driving wheels of each truck are coupled directly to a jack-shaft, which is twin-geared to a pair of three-phase induction motors. Fig. 349A shows the arrangement of the motors and gearing.

Heavier (185-ton) locomotives, recently built, are also of the two-unit type and each unit has two pairs of driving axles, but the four axles are fitted into a common framing, the rigid wheel-base being 16 ft. 6 in. The driving wheels are coupled in pairs, and each pair is separately driven from a jack-shaft by horizontal connecting rods. Each jack-shaft is driven through flexible twin-gearing from a single motor of 1000–1200 h.p.

The motors of both locomotives have pole-changing stator windings (8/4 poles) and double rotor windings. They are controlled by liquid

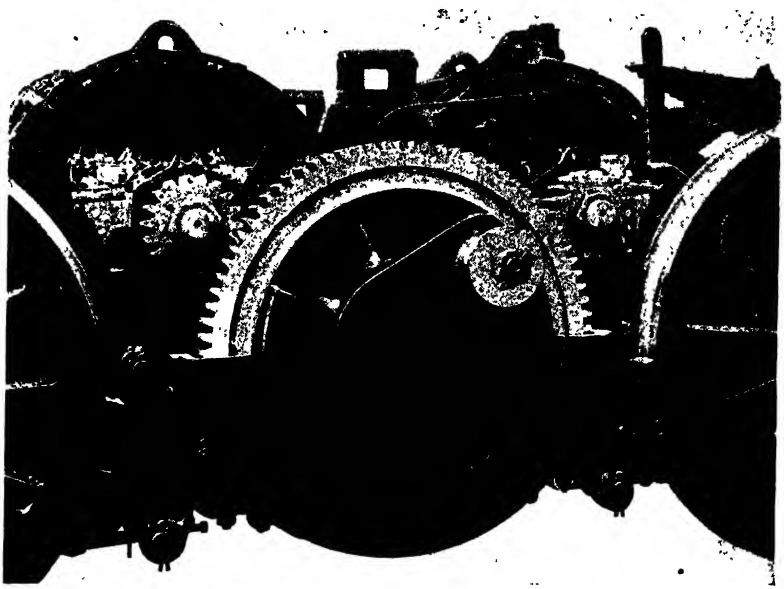


FIG. 349A.—Truck with Motors and Gear-driven Jack-shaft for Norfok and Western Locomotive.

rheostats, and during starting provision is made for reducing, when necessary, the torque of any motor, or pair of motors, as the case may be, without affecting the torque of the other motors. Thus in the event of one pair of driving wheels slipping the torque of the corresponding motor, or motors, can be reduced until the slipping ceases, when the normal torque can be restored. To prevent the complete loss of tractive effort momentarily when changing the number of poles, this operation is effected in two steps, each step involving only one-half of the number of motors on the locomotive.

The phase converter originally was of the induction type, but the synchronous type is employed in the more recent locomotives to enable the power factor to be controlled and maintained at about 0·95. In each case the converter is started by a single-phase commutator motor. Tappings on the transformer, together with a contactor-type tap-changer, enable normal voltage to be obtained on the three-phase side of the phase converter when the (single-phase) trolley-wire voltage is below normal, a

variation of 15 per cent of the normal voltage (11,000 volts) being provided for.

Composite locomotives. The term "composite" locomotive is applied to a locomotive equipped with direct-current motors and supplied with energy from a single-phase system. Such a locomotive, therefore, must be equipped with converting plant of the rotating (motor-generator) type.*

An experimental locomotive of this type was built by the Oerlikon Co. in 1905 for working from a 15,000-volt, 50-cycle, single-phase system, but the development was then dropped owing to the evolution of the low-frequency single-phase commutator motor, which was able at that period to satisfy the requirements of railway electrification. However, present-day requirements in the electrification of mountain-grade railways handling heavy traffic have necessitated the development of extremely powerful

FIG. 350.—Composite (Motor-generator) Locomotive in Service on Gt. Northern Railway. (General Electric Co., Schenectady.)

locomotives, the full capacity of which can be utilized for both propulsion and regenerative braking. One solution is the "split-phase" locomotive, and another solution is the "composite" locomotive. The latter type of locomotive possesses a number of advantages over the split-phase locomotive, and has been adopted for the recently electrified lines of the Great Northern Railway in the Cascade Mountains.†

Fig. 350 shows one of the **Great Northern** locomotives (Reference No. 25), designed and equipped by the General Electric Co., Schenectady. The body is mounted upon two articulated trucks, each having three driving axles and a radial pony axle. A detail view of one of the trucks is given in Fig. 350A, which shows the single steel casting combining the side-frames, end-frames, transoms, and air (ventilating) trunk. Each

* The mercury-arc rectifier is unsuitable on account of its non-reversibility and its operation being affected by vibration.

† For details, see *Transactions A.I.E.E.*, vol. 48, p. 40. Previous to this electrification a Westinghouse locomotive (340 tons, 4200 h.p.) was in service on the 17-mile, single-track, Detroit, Toledo and Ironton Railway for handling freight traffic between the works of the Ford Motor Co. Details are given in the *Tramway and Railway World*, vol. vii, p. 187.

driving axle is twin-geared to a 550-h.p., 750-volt, axle-mounted motor, and the trucks are designed to permit the removal of a complete motor and axle into a pit.

The six motors are permanently connected in series-parallel; there being three groups, each consisting of two motors connected in series. When motoring, they are controlled by varying the applied voltage and by shunting the field windings. Regenerative braking is obtained by separately exciting the field windings; electrical stability being obtained

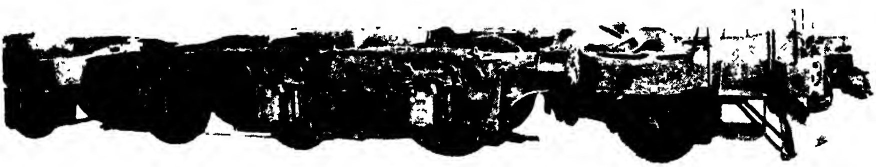


FIG. 350A.—One of Trucks of Locomotive illustrated in Fig. 350, showing One-piece Steel Casting combining Side Frames, End Frames, Transoms, etc.

by means of stabilizing resistances. Control of the braking torque is effected by varying the excitation of the traction motors, and, if necessary, that of the main generators also.

The motor-generator set, Fig. 350B, runs at a speed of 750 r.p.m. and consists of a 3500-h.p., 2300-volt, 25-cycle, synchronous motor, coupled

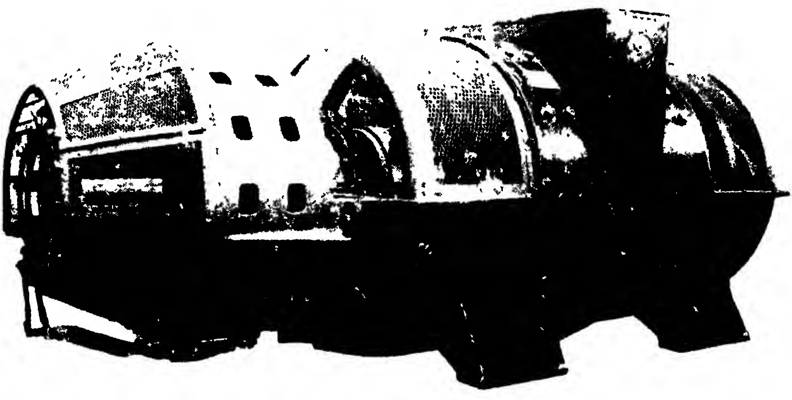


FIG. 350B.—Part of Motor-generator Set (Direct-current Generators and Combined Starting Motor and Regenerative Exciter) for Locomotive illustrated in Fig. 350. NOTE.—The synchronous motor and main exciter form a separate unit, which is connected to the above by a flexible coupling.

to: (1) a 2500-kW., 1500-volt, direct-current, separately-excited generator (consisting of two 750-volt machines connected permanently in series), (2) a 65-volt exciter for the synchronous motor, generator, and control-circuit supply, (3) a dual machine which can operate either as a single-phase series motor (for starting the set) or as a direct-current generator (for exciting the traction motor field windings during regenerative braking).

The synchronous motor is started by supplying current to the starting motor; the transformer being provided with a special (150-volt) winding for this purpose on account of the heavy starting current (4000 amperes). When the speed reaches about 80 per cent of synchronous speed (which condition is indicated by the building-up of the exciter) the stator is connected to the 1800-volt tapping of the transformer. The motor then runs up to synchronous speed, and, when it pulls into step, the stator is transferred to normal voltage; excitation is applied, and the starting motor is disconnected. All operations are effected automatically.

The transformer is of the air-blast type and is rated at 3285 kVA. It weighs 26,850 lb.; is installed on its side; has overall dimensions 88 in. by 53½ in. by 78 in. high, and requires 7000 cu. ft. of air per minute (at 40° C.) at a pressure of 0·125 lb. per square in.

The auxiliary apparatus comprises: two air compressors; two blower sets for the transformer; a blower set for the traction motors; a 65-volt storage battery for emergency lighting and for supplying the control circuits of the electro-magnetic contactors controlling the starting motor of the motor-generator set and the air-compressor motors. The motors of the air-compressors and transformer blower sets are of the single-phase repulsion-induction type, but the motor driving the blowers for the traction motors is of the three-phase induction type, and is supplied from the synchronous motor, the stator of which is wound with three phases.

The control system provides for 24 operating voltages, two shunted-field steps when motoring, and 16 values of excitation for regenerative braking. Electro-pneumatic contactors are employed, and, except for the shunted-field steps, are connected in the shunt-field circuits of the generator and regenerative-braking exciter. The master controller has three handles which control (1) the reversers, (2) the operating voltage, (3) the excitation during regenerative braking.

The Westinghouse locomotives in service on the Great Northern Railway are designed for a lower operating speed and differ in a number of details from the General Electric locomotives. For example, there are four driving axles; the four motors (each 540 h.p., 600 volts) are connected permanently in parallel and are supplied from a single 1500-kW., 600-volt generator; the motor-generator set is started from a 125-volt storage battery; field control of the traction motors is employed during motoring at full voltage, the field windings of the traction motors being separately excited from a special exciter.

CHAPTER XVIII

TRAIN RESISTANCE

TRAIN resistance is the term applied to the forces resisting the motion of a train when it is running at uniform speed on a straight and level track. Under these conditions the whole of the energy output from the driving axles is expended against train resistance. Thus a portion is expended against friction internal to the rolling stock (which consists of friction at the journals, guides, bogies, buffers, etc.) ; another portion is expended against the external resistances between the rolling stock and the track (e.g. rolling friction between the wheels and rails, flange friction between the wheels and rails, resistances resulting from the temporary deflection of the track due to the passage of the train over it) ; and the remaining portion is expended against air resistance.

Components of train resistance. The internal and external resistances together constitute the **mechanical resistance** component of train resistance. These resistances do not admit of detailed analysis on account of their varied and uncertain nature. For example, flange friction depends largely upon accidental conditions such as oscillation of the coaches, lateral wind pressure, etc., while the track resistance is influenced by the condition of the track, the strength of the rails, and the nature of the ballast.

It is probable that some of these resistances increase with the speed, while others may be unaffected or may even decrease with the speed. At low and moderate speeds (between 5 ml.p.h. and 40 ml.p.h.) we are probably correct in assuming that the mechanical resistance increases directly with the speed,* but at higher speeds there is evidence to show that this relation does not hold good. In fact the train-resistance tests† carried out on the Marienfelde-Zossen experimental track indicate that, for the particular coaches experimented with, the mechanical resistance is practically constant between speeds of 90 and 125 ml.p.h. At these high speeds, however, the train resistance consists principally of air resistance, and the mechanical resistance is only a small fraction of the total.

The mechanical resistance is generally assumed to be proportional to the weight of the train, which assumption, for a given class of rolling stock, is probably correct. Experiments have demonstrated that less tractive effort per ton of train weight is required to haul trains composed of heavy rolling stock than similar trains composed of light coaches, other conditions being equal. A similar result has been obtained in certain tests with bogie freight wagons, where the tractive effort per ton of train weight required to haul a train of loaded wagons was only 56 per cent of that required to haul the same train of empty wagons over the

* This law does not hold good for the very low speeds incidental to starting, as the resistance under these conditions is very much greater than that at speeds above 4 to 5 ml.p.h.—due to increased track resistance and journal friction.

† See *Journ. I.E.E.*, vol. 33, p. 894. Paper on "High-speed Electric Railway Experiments on the Marienfelde-Zossen Line."

same track under similar conditions of speed.* An explanation of this phenomenon is that the flange friction of a bogie truck is reduced by an increase of load.

The **air resistance** is generally assumed to vary as the square of the velocity of the train; and may be divided into two components, viz. one associated with the ends of the train and the other with the length of the train. The former includes the head resistance and the suction effect at the rear, while the latter includes the air friction on the sides, top, and underside of train, and is termed "skin friction."

The **head resistance** depends upon the exposed surface at right angles to motion: it is largely influenced by the shape of the leading portion

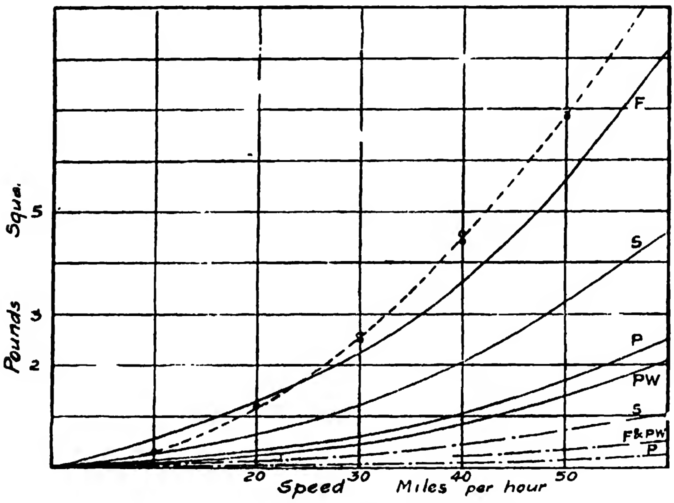


FIG. 351.—Air-resistance Curves for Motor Coach with various types of Vestibules: *F*, flat end; *S*, partially rounded (standard U.S.A.); *P*, parabolic; *PW*, parabolic wedge. NOTE.—Full lines show the head resistance; chain dotted lines show the suction resistance. The dotted curve is drawn through points calculated from equations: $p = 0{\cdot}0028 V^2$ and $p = 0{\cdot}003 V^2$.

of the train and the direction and velocity of the wind. With trains hauled by locomotives the largest portion of the head resistance is encountered by the locomotive, but with electric trains operated with motor coaches and trailers the whole of the head resistance is encountered by the leading coach. By suitably shaping the end of this coach, it is possible to obtain a considerable reduction in head resistance.

The **suction resistance** is also affected by the shape of the end coach, but as the magnitude of this resistance is only about one-tenth of the head resistance, the shape of this portion of the train is not so important as that of the opposite (or leading) end.

The manner in which air resistance is influenced by the contour of the front and rear portions of the train is shown by the curves of Fig. 351. These curves indicate the results obtained by the St. Louis Railway Test

* *Railroad Gazette*, vol. 31, pp. 207, 262. Also a paper on "Predetermination of Train Resistance," by Prof. C. A. Carus Wilson (*Min. of Proc. I.C.E.*, vol. 171, p. 227).

Commission* on an experimental motor coach fitted with vestibules of different forms, viz. (1) flat; (2) partially rounded (the standard type on U.S. inter-urban cars); (3) parabolic; (4) parabolic wedge, the relative shapes being shown in Fig. 352.

The **skin-resistance** component of the air resistance depends on the length of the train, the type of coaches, the nature of the external fittings, projections, etc. It is affected to some extent by side winds, but there is very little data available to indicate the effect of side winds or other conditions on the skin resistance. In the case of long trains, skin resistance becomes an important item in the air resistance; and

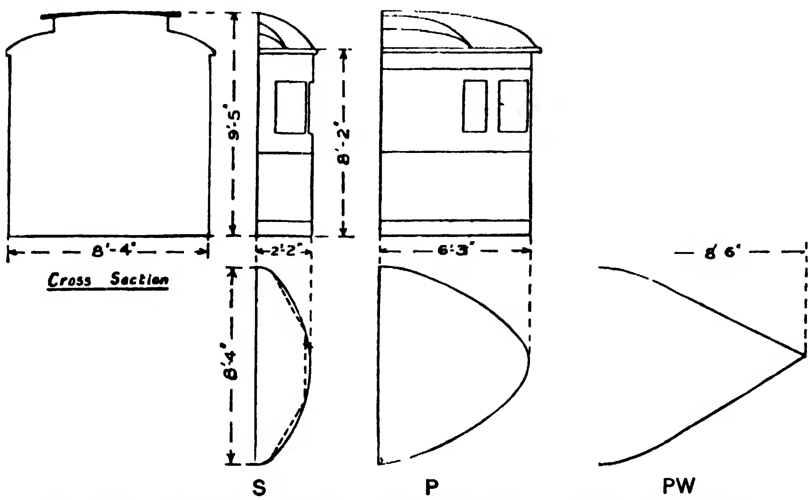


FIG. 352.—Types of Vestibule used for Air-resistance Tests of Fig. 349.

even for short trains it cannot be neglected, especially when the leading portion of the train is shaped to give the minimum head resistance.

As the air resistance depends entirely on the external configuration of the train, lightly-built coaches—such as the rolling stock used for the suburban services of some steam railways—will have practically the same air resistance as coaches, of much heavier construction, which form the rolling stock on the main lines of our large railways.

Methods of determining train resistance. The methods of conducting train resistance tests with steam trains are: (1) by determining the draw-bar pull of the locomotive and the speed of the train under conditions of uniform speed; (2) by allowing the train to coast (without the locomotive), and obtaining an accurate record of the retardation.†

* *Report of Electric Railway Test Commission* (St. Louis), p. 534. The car on which the air resistance tests were conducted had the following dimensions: Length over corner posts, 32 ft.; width, 8 ft. 4 in.; height from side sills to top of roof, 9 ft. 5 in.; projected area of each vestibule (at right angles to motion), 96 sq. ft. The car body was specially mounted on dynamometers, so that the total resistance and the head resistance could be measured directly.

† The retardation can be determined directly by the Wimperis accelerometer (see p. 165), which is made with ranges suitable for train-resistance tests.

The first method requires a dynamometer car, and has the disadvantage that only a portion of the head resistance is included in the dynamometer reading. This disadvantage is not apparent when considering trains hauled by locomotives, as the largest portion of the head resistance is encountered by the locomotive, and would be included in the resistance of the locomotive. The train resistance is equal to the draw-bar pull, which, together with the speed, is recorded graphically. The records should, preferably, both be on the same chart.

The second method has the drawback (which is associated with all coasting tests on trains) that the whole of the head resistance is encountered by the leading coach, and therefore the retarding force on this coach is greater than that on the following coaches. Consequently there is a tendency for the coaches to crowd together, which produces greater oscillation and flange friction than when the couplings are tight. The train resistance is obtained from the retardation in the following manner—

The force necessary to produce a retardation of 1 ml.p.h.p.s. on an effective weight of 1 ton is 102 lb. (p. 28). Hence, if β_c is the retardation in ml.p.h.p.s., and W_e is the effective weight of the train, the total retarding force will be $102\beta_c W_e$ lb., which will be equal to the train resistance, provided that the train is on a level track. It is essential that the contour of the track be accurately known, as an "up" gradient of 1 in 1000 corresponds to a retarding force of $2\frac{1}{4}$ lb. per ton of train weight.

The effect of gradients can be eliminated by using an ergometer, by which instrument a record is obtained of the total work done against resistances other than gravity. The train resistance is then obtained by dividing the work done by the distance traversed.

With electric trains the total train resistance can be determined by observing the voltage and current input to the motors when the train is running at uniform speed. The tractive effort and speed can then be deduced from the characteristic curves of the motors: the tractive effort will correspond to the train resistance, provided that the train is on the level and is not being accelerated.

With the usual motor equipment the free running speed of the train occurs on the steep portion of the speed curve of the motor, so that a small error in reading the current may result in a relatively large error in the speed. Moreover, as free running is approached very slowly with the full motor equipment, a long stretch of level track would be required in order to eliminate the above sources of error. This objection can be overcome by using a train with a small motor equipment. Thus, with several motors controlled on the multiple-unit system, the train can be accelerated, by the whole equipment, to approximately the speed required, and then a number of motors may be cut out, so that the train may be kept running at uniform speed.

The coasting method of determining train resistance may also be used with electric trains. In this case, however, the total resistance to motion includes not only the train resistance, but also the friction in the motors and gears, which, in trains equipped with several motors, may amount to a considerable percentage of the total resistance. The effect of the revolving parts (armatures, gears, and wheels) must be taken into

account in deducing the train resistance from the observed retardation, as the stored energy in these parts may, in some cases, amount to over 10 per cent of that for the whole train.

Train resistance formulae. In view of the large number of variables involved in train resistance, it is not surprising to find a large number of formulae of varied forms to express the law of variation of train resistance with speed. These formulae, when applied to a given train, will be found to give widely divergent results. Hence train resistance formulae must be used with discrimination, as, although each formula may be correct for the conditions under which it was derived, the probability of similar conditions for the tests of different investigators is very remote. Such items as the type of coach, the nature of the track, and the method of testing would be quite sufficient to cause large variations in the results.

In this country we are indebted to Sir John Aspinall for most of our data on train resistance. **Aspinall's tests*** were made with main-line oil-lubricated bogie coaches on the Lancashire and Yorkshire Railway (now part of the London, Midland and Scottish Railway), the dynamometer car method being used. An attempt was made to use the coasting method, but the results obtained were so erratic that they were discarded. A very large number of tests were made with a train composed of five bogie coaches and a dynamometer car. Tests were also made with trains composed of 10, 15, and 20 coaches. The results of the tests are represented in Fig. 353, and the following law for the train resistance between speeds of 10 and 80 ml.p.h. was deduced by Aspinall -

$$r = 2{\cdot}5 + V^{5/3}/(51 + 0{\cdot}0278L) \quad . \quad . \quad . \quad . \quad . \quad (33)$$

where r is the specific train resistance† in lb. per ton of train weight, V is the speed in miles per hour, and L is the length of the train in feet.

The train resistance at speeds below 10 ml.p.h. follows a different law. For instance, in the tests on the five coach train, the average resistance at starting was found to be 17 lb. per ton, which rapidly decreased to about 3 lb. per ton at a speed of 5 ml.p.h., and then increased slowly with increasing speed.

It should be noted that the above tests were made with coaches hauled by a steam locomotive, so that the formula only gives the head resistance for that part of the coach not shielded by the locomotive.

Aspinall also made tests to determine the magnitude of the head resistance by measuring the air pressure on the exposed portion of the coach. The results obtained indicate that the air pressure p (expressed in lb. per square foot of exposed surface at right angles to the direction of motion) follows the law $p = 0{\cdot}003\ V^2$, where V is the speed in ml.p.h.

* Paper by Sir John Aspinall on "Train Resistance" (*Min. of Proc. I.C.E.*, vol. 147, p. 155). A collection of formulae is given on pp. 189–192.

† The customary method of expressing train resistance is in *lb. per ton of train weight,* which may be termed the "specific train resistance."

For moderate speeds this method provides a suitable means for comparing the results of tests and for estimating purposes. But, for high speeds, where the air resistance is the principal component of the train resistance, the above method is no longer suitable, since it is liable to lead to erroneous conclusions when applied to trains of different weights.

A similar result has been obtained in the Marienfelde-Zossen high speed tests, but in this case the coefficient was found to be 0·0028.

The results of these air-pressure measurements are represented by the dotted curve in Fig. 351. In comparing this curve with that given for the flat vestibule, it should be noted that the latter was derived by measuring the total pressure on the vestibule, whereas in the above tests an indirect method was used. It is probable that the lower results

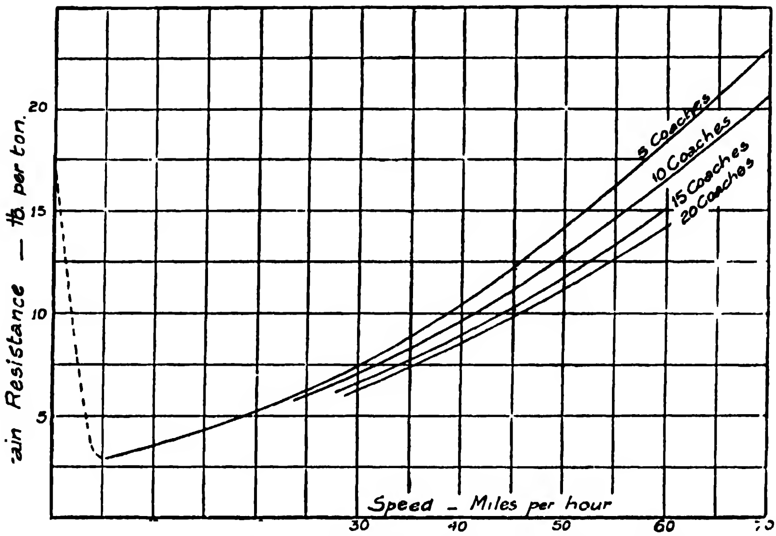


FIG. 353.—Results of Aspinall's Tests for Train Resistance.

indicated by the St. Louis tests are due to a falling-off of the pressure at the edges of the vestibule.

General equations for train resistance. From a consideration of the separate components of train resistance, we should expect the law of variation of resistance with speed to be of the form—

$$R = a + bV + cV^2$$

where R is the total train resistance in lb., V is the speed of the train in ml.p.h., and a, b, c are constants related to the particular train and track. In this equation the first two terms represent the mechanical resistances and the last term represents the air resistance.

(*a*) *Locomotive-hauled trains.* The author has examined the results of Aspinall's tests to ascertain if they conform to the law

$$R = a + bV + cV^2.$$

It was found that the curves closely approximated this law, and the following equations were obtained for the 5, 10, and 20 coach trains—

5 coach train: $R = 230 + 10{\cdot}3V + 0{\cdot}322V^2$
10 coach train: $R = 402 + 20{\cdot}6V + 0{\cdot}547V^2$
20 coach train: $R = 800 + 35{\cdot}2V + 0{\cdot}86V^2$.

As the last term in these equations represents the air resistance, we

can, by estimating the head and suction resistances, arrive at an approximate value for the skin resistance. Moreover, this value may be checked by determining the difference in the air resistances for trains of different lengths. Treating the tests on the 5 coach and 10 coach trains in this manner, we obtain, for the skin resistance, an average value of $0{\cdot}000035V^2$ lb. per square foot of longitudinal exposed surface.

For coaches with elliptical roofs, of the usual proportions on the main line railways of this country, the longitudinal exposed surface (S) per coach is given approximately by

$$S \text{ (square feet)} = 0{\cdot}35LA$$

where L is the length of the coach in feet and A is the transverse cross-section of the coach body in square feet.

Hence, if the head resistance is taken at $0{\cdot}0028V^2$ lb. per square foot of transverse exposed surface, the coefficient c in the general equation for train resistance becomes

$$\begin{aligned} c &= 0{\cdot}0028kA\lambda + 0{\cdot}0000122nLA \\ &= A(0{\cdot}0028k\lambda + 0{\cdot}0000122nL) \quad . \quad . \quad . \quad (34) \end{aligned}$$

where k is a coefficient to include the effect of the shape of the end of the coach (see below), λ* is the ratio exposed transverse surface/cross-section of coach body, n is the number of coaches in the train, L is the length of each coach in feet, and A is the transverse cross-section of the coach body in square feet. The following values, based on the curves of Fig. 351, may be taken for k.

Type of End of Coach (*see Fig.* 352)	k
Flat	1·0
Partially rounded (Standard U.S. inter-urban cars).	0·65
Parabolic	0·3
Parabolic wedge	0·28

A general expression for the total mechanical resistances can be obtained from the above equations for the resistances of 5, 10, and 20 coach trains. Thus the total mechanical resistances (in lb.) for a train of W tons $= W\{1{\cdot}8 + V(0{\cdot}185 - 0{\cdot}0393 \log W)\}$.

Hence, for trains consisting of trailer bogie coaches (main-line stock, with oil-lubricated journal boxes) running on good track, the train resistance may be estimated from the general formulae—†

$$R = W\{1{\cdot}8 + V(0{\cdot}185 - 0{\cdot}0393 \log W)\} + AV^2(0{\cdot}0028k\lambda + 0{\cdot}0000122nL) \quad (35)$$

$$r = 1{\cdot}8 + V(0{\cdot}185 - 0{\cdot}0393 \log W) + AV^2(0{\cdot}0028k\lambda + 0{\cdot}0000122nL)/W \quad (36)$$

R being the total resistance in lb., and r the specific train resistance in lb. per ton of train weight.

This formula is not suitable for electric motor-coach trains, as the resistance of these trains is considerably higher than that of trains operated with locomotives.‡

* This term is introduced to include the shielding effect of the locomotive. For motor-coach trains $\lambda = 1{\cdot}0$.

† All formulae for train resistance refer to still-air conditions. In gusty weather the resistance will be greater, due to the increased air resistance.

‡ The resistance of locomotive-hauled trains under steam railway conditions is discussed at length in a series of articles, entitled "The Resistance of Express Trains," by C. W. Dendy Marshall, in the *Railway Engineer*, Jan.-Nov., 1924.

(*b*) *Motor-coach trains.* The increased resistance of motor-coach trains is manifested by the greater wear which these trains produce on the track rails,* and may be accounted for by (*a*) the heavy weight of bogie trucks with motors, (*b*) the unspring-borne weight on the axles of the motor trucks, (*c*) the low centre of gravity of the motor coaches, (*d*) the small diameter of the driving wheels. These conditions are not conducive to good riding qualities, and, in consequence, a large amount of flange friction and "nosing" (lateral oscillation) takes place, while the track is subjected to direct blows of considerably greater magnitude than those which occur with locomotive hauled trains of trailer coaches.

As far as the author is aware, no tests have been made for the determination of the magnitude of these increased resistances. Tests have been made, however, on motor-coach trains,† but in all cases the coasting method has been adopted.

Now it is extremely important to remember that, for electric trains consisting of motor coaches and trailers, there are *two train resistances* to be considered, viz. (1) the *true train resistance* when the power is "on"; (2) the *apparent train resistance* when the power is "off" and the train is coasting. In the latter case the motors are being driven by the train, and, in addition to the true train resistance, there is the friction losses in the motor-axle bearings, gears, armature bearings, brushes, and the windage loss in the motors. These losses are all attributed to the motors when the power is "on" (the characteristic curves of the motors being calculated for the output at the tread of driving wheels), and it would be impracticable to do otherwise, as the loss in the gearing will necessarily depend upon the power being transmitted.

The additional retarding force due to motor and gear friction depends upon the size and type of motor, the number of motors per train, the gear ratio, and the diameter of the driving wheels. In the case of trains operating on urban railways, where the motors are geared for a low free-running speed, the motor and gear friction may be of the order of from 4 to 5 lb. per ton of train weight. For suburban trains, operating at higher speeds, the motor and gear friction, at free-running speed, may be of the order of from 2 to 3 lb. per ton.

In order to derive a formula for the resistance of motor-coach trains, the author has analysed the curves which have been published‡ for the electric trains on the Liverpool–Southport section of the London, Midland and Scottish Railway. Corrections have been applied for motor and gear friction and the effect of head winds. The corrected curve for the resistance of a two-coach train (consisting of one motor coach and one trailer coach) is plotted in Fig. 354, and follows the law

$$r = 4{\cdot}1 + 0{\cdot}055V + 0{\cdot}0045V^2,$$

where r is the specific train resistance in lb. per ton of train weight, and V is the speed in ml.p.h.

* See *Min. of Proc. I.C.E.*, vol. 179, pp. 99, 143; vol. 197, p. 79. *Proc. I.M.E.* (1909), p. 438.

† See Sir John Aspinall's Presidential Address to The Institution of Mechanical Engineers (*Proceedings*, 1909, p. 473). Also *Journ. I.E.E.*, vol. 50, p. 453; vol. 52, p. 446. *Min. of Proc. I.C.E.*, vol. 186, p. 46.

‡ See *Proc. I.M.E.* (1909), p. 473; *Journ. I.E.E.*, vol. 52, p. 446. The author is indebted to Lt.-Col. O'Brien for data of the latter tests.

Now a general formula for the resistance of motor-coach trains should discriminate between trains made up of motor coaches only and those made up of motor coaches and trailers. At the present time, however, there is not sufficient data available to enable this distinction to be made. Moreover, on some lines it is the general practice to operate one motor coach with one or two trailer coaches as a "train unit," the train being composed of one or more "train units."

A general equation, derived from Fig. 354, however, will enable the train resistance of motor-coach trains to be estimated with sufficient accuracy, especially since the use of this class of train is restricted to

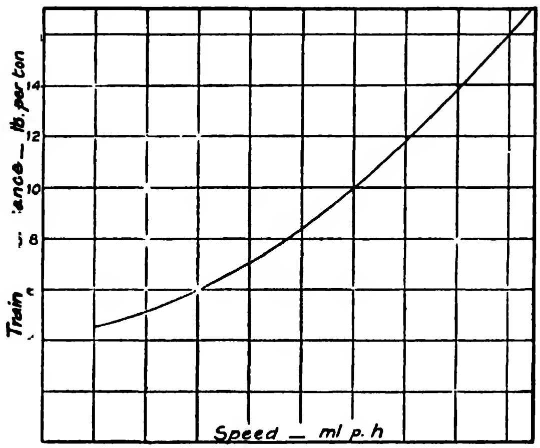


FIG. 354.—Corrected Curve for the Resistance of a Two-coach Electric Train.

urban and suburban services, in which the free-running period (if any) is only a small fraction of the total running period.

The general equation* derived from Fig. 352 follows the law

$$R = W(4{\cdot}1 + 0{\cdot}055V) + AV^2(0{\cdot}0028k + 0{\cdot}0000122nL) \quad . \quad (37)$$

or $$r = 4{\cdot}1 + 0{\cdot}055V + AV^2(0{\cdot}0028k + 0{\cdot}0000122nL)/W \quad . \quad . \quad (38)$$

where the symbols have the same significance as in previous equations.

Electric locomotive and train (American coaches). An extended investigation on this subject has been carried out by Dr. F. W. Carter,† using the results obtained during the 50,000 mile endurance tests on the original New York Central gearless locomotives built by the General Electric Co., Schenectady. Some hundreds of runs were made with trains composed of different numbers of coaches, of the standard American saloon type—some of the trains consisting of four-wheel bogie coaches (55 ft. long overall, 47 ft. 6 in. over body, 9 ft. 11½ in. width, 13 ft. 6½ in. overall height, 36 in. wheels, loaded to 26·2 tons), and others consisting of six-wheel bogie coaches (66 ft. long overall, 60 ft. 2 in. over body,

* In these equations the value of k should be chosen from 15 per cent to 20 per cent higher than the values given on p. 498 to allow for the increased air resistance caused by the motors.

† *Min. of Proc. I.C.E.*, vol. 201, p. 243.

9 ft. 11½ in. in width, 13 ft. 8½ in. overall height, 36 in. wheels, loaded to 45·3 tons).

The investigation showed that the resistance of the locomotive and train at a given speed was a function of the number of coaches, the relationship between total tractive resistance at a given speed and number of coaches following a straight line law for trains consisting of two or more coaches. Moreover, the relationship between the resistance for each coach added to the train and the speed was also found to be a straight line. Thus if n is the number of coaches in the train, the tractive resistance in lb. due to these coaches is given by $n(100 + 5{\cdot}22V)$ for the

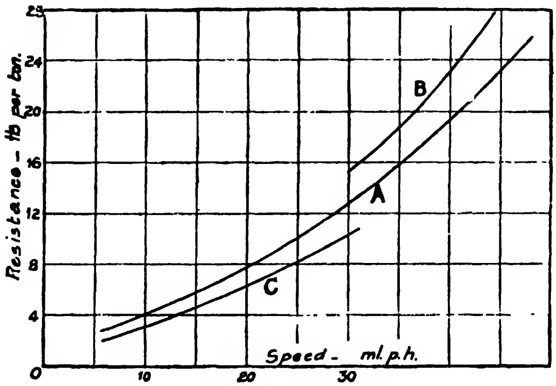


FIG. 355. Resistance of 2–6–2 Electric Locomotive and Train in the Simplon Tunnel.

A. Without forced ventilation in tunnel.
B. With forced ventilation in tunnel — Motion of train opposite to direction of ventilating air.
C. With forced ventilation in tunnel — Motion of train in same direction as ventilating air.

66 ft., 6-wheel, bogie coaches, and $n(84 + 4{\cdot}28V)$ for the 55 ft., 4-wheel, bogie coaches.

Train resistance in tunnels. The resistance of trains in tunnels is naturally higher than that of trains in the open on account of the increased air resistance. The effect of forced ventilation (such as is required in very long tunnels) will also have a considerable influence on the train resistance. In this connection the curves of Fig. 355* (which refer to the conditions obtaining in the **Simplon Tunnel**) are of interest. These curves give the resistance of a train and locomotive when running through the tunnel under different conditions of ventilation. The electric locomotive was of the 2–6–2 gearless type with scotch-yoke drive; its weight was 62 tons, and the transverse cross-section 102 sq. ft. The cross-section of the tunnel was 253 sq. ft. The train (including the locomotive) weighed 327 tons and was 666 ft. long.

In **tube railways,** where the clearance between the train and the tube is very small, the train resistance will be considerably affected by the increased air resistance, which in this case is practically all head resistance.

* From a paper by E. Thomann on "The New Electric Locomotives for the Simplon Tunnel." See *Genie Civil,* July, 1909.

From tests carried out on the **Central London Railway**, the specific train resistance was found to follow the law $r = 6 + 0{\cdot}5V^2/W$.* At a speed of 20 ml.p.h., the resistance of a 130 ton train (with seven cars) is 7·5 lb. per ton, while, in the open, the resistance at this speed—calculated from Aspinall's formula—is only 4·8 lb. per ton.

Train resistance at curved track. This is greater than the resistance on straight track, due to greater flange friction, etc. The additional resistance will depend upon the radius of the curve, the wheel-base of the trucks, and the end play between the wheel flanges and the rails. Very little data is available on the resistance at curved track,† which is probably due to the fact that to obtain accurate results a long stretch of track of uniform curvature is required.

A method adopted by American engineers for estimating the additional resistance at curves is to consider that each degree‡ of curvature increases the train resistance 0·6 lb. per ton (2000 lb.) of train weight. In this country curves are usually expressed in terms of the radius (R), and if this is given in feet the additional train resistance will be

$$0{\cdot}6 \times (2240/2000) \times 2 \sin^{-1}(50/R) = 1{\cdot}35 \sin^{-1}(50/R) \text{ lb. per ton.}$$

Tractive resistance of tramcars and railless cars. The preceding formulae all refer to the resistance of trains operating on railways where the track can be maintained in good condition. The resistance of tramcars operating through streets will be much higher than that of railway trains, on account of the different condition of the track and of differences in the construction of the cars and trucks.

The nature of the service on tramways and the low operating speeds, however, do not warrant an accurate estimation of the resistances to

* *Proc. I.M.E.* (1912), p. 940. Mr. W. Casson (in a discussion on "The Dynamical Diagrams of a Train") states: "To show the effect of the increased air resistance in the tunnel . . . a single motor-car took just half the current and ran at the same speed as a train of seven cars, of which two were motor-cars, the speed being 27 ml.p.h. in each case. At this speed the tractive effort for the single car was 1000 lb., and that for the seven-car train was 2000 lb.

"From the Aspinall formula (33), the resistances of the car and the train would be, respectively, 7·2 and 6·65 lb. per ton, giving totals of 166 and 770 lb. There was, therefore, an additional total resistance, due to running in the tube, which was obviously independent of the weight of the train. . . . This additional resistance amounted to 834 lb. for the single car and 1230 lb. for the train."

[*Author's Note.*—From these values we obtain 768 lb. for the head and suction resistances, 66 lb. for the skin friction of the single car, and 462 lb. for the skin friction of the seven-car train.]

"It was interesting to note that 768 lb. was about 8·5 lb. per square foot of cross-sectional area of the train. A water-gauge showed 1·5 in. difference of level between the back and front of the train, corresponding to 7·8 lb. per square foot."

† Some test results obtained on the City and South London Railway are given by Mr. McMahon in the *Min. of Proc. I.C.E.*, vol. 147, p. 215. The tests refer to a tube railway with a very light train and small wheels. The results indicate that a large increase in the train resistance occurs at a sharp curves; for instance, on a curve of 540 ft. radius the resistance at a speed of 13·5 ml.p.h. was found to be 22·6 lb. per ton, while the resistance at this speed on straight track was only 11·3 lb. per ton. The additional resistance at the curve corresponds to 1·06 lb. per 1° of curvature.

‡ In this system curvature is given by the angle (in degrees) which a chord 100 ft. long subtends at the centre of curvature. Hence if θ is the curvature in degrees and R is the radius of the curve in feet, then $\sin \tfrac{1}{2}\theta = 50/R$, or $\theta = 2 \sin^{-1} 50/R$.

motion, and an average value of 25 lb. per ton may be assumed for general conditions.*

With **railless cars** the resistance will be affected largely by the nature of the road surface and the class of tyres. On account of these indefinite conditions the values obtained for the resistance of motor vehicles can

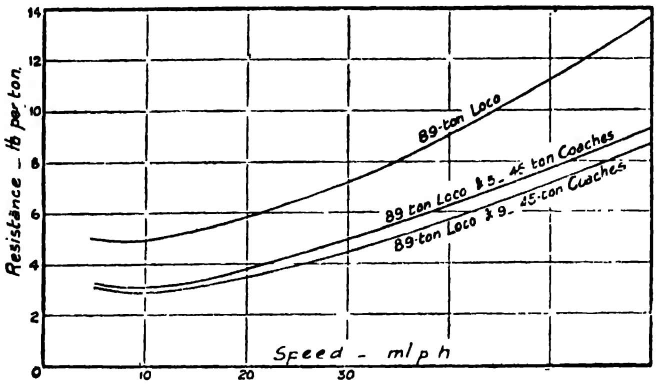


FIG. 356.—Resistance of "New York Central" Type of Gearless Locomotive (with Bipolar Direct-current Motors).

only be considered as a rough approximation to the average resistance. Careful tests† on a commercial electric (battery) vehicle with solid rubber tyres and a back-axle drive have shown that on asphalt, macadam, and

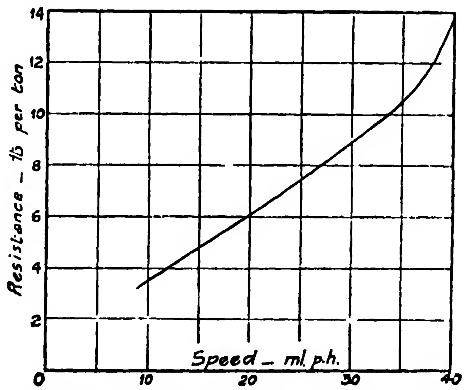


FIG. 357. Resistance of 61-ton, 2–6–2 Gearless Locomotive with Side-rod (Scotch-yoke) Drive.

wood paving in good and dry condition the tractive resistance is between 20 and 30 lb. per ton at a speed of 12 ml.p.h. With the surface in poor condition, the resistance may be of the order of 50 lb. per ton.

Tractive resistance of electric locomotives. An approximation to the tractive resistance of a locomotive can only be made when tests on a

* *Min. of Proc. I.C.E.*, vol. 198, p. 24.

† *Trans. A.I.E.E.*, vol. 35, p. 925 (Tests on ½-ton Electric Delivery Van).

locomotive of a similar type are available, as, on account of the variety of designs, it is impossible to derive formulae suitable for general application. Moreover, the resistance of a locomotive running light is of interest only for comparative purposes, as when a locomotive is coupled to a train the resistance attributable to the locomotive is not the same as that when running light.*

The curves in Figs. 356, 357, which give the resistances of two different types of locomotives, are of interest for comparative purposes. Fig. 356 refers to a gearless locomotive equipped with bipolar direct-current motors, and having four driving and two pony axles. The weight of the locomotive was about 90 tons, the load on each driving axle was 16·7 tons, and the dead weight on each driving axle was 5½ tons. The body was of the box type, being 34 ft. long, 10 ft. wide; and the roof was 13 ft. 9 in. above the rails. The driving wheels were 44 in. in diameter, and the rigid wheel base was 13 ft.

Fig. 357 refers to a gearless locomotive with scotch-yoke drive.† In this case the (two) motors were frame-mounted and were directly coupled to the central pair of driving wheels by scotch yokes, to which the other driving wheels were coupled by side rods. The weight of the locomotive was 61 tons, of which 41 tons were carried on the three driving axles and the remaining 20 tons on pony axles. The driving wheels were 59 in. in diameter and the coupled wheel base was 15 ft. 5 in. The body was constructed with a central cab and sloping ends; the dimensions of the body being: overall length, 31 ft. 4 in.; length of central cab, 20 ft.; width of central cab, 9 ft. 4 in.; height of roof above rails, 12 ft.; width of sloping ends, 7 ft. 4 in.; heights of sloping ends above rails, 7 ft. 1 in. (min.), 8 ft. 2 in. (max.).

* *Min. of Proc. I.C.E.*, vol. 201, p. 243.

† From a paper by F. Koromzay on "The New Electric Locomotives of the Valtellina Railway" (*Revue Generale des Chemins de fer*, March, 1905).

CHAPTER XIX

THE CALCULATION OF SPEED-TIME CURVES AND ENERGY CONSUMPTION FOR ELECTRIC TRAINS

PART I—SPEED-TIME CURVES

THE importance of the speed-time curve in electric railway engineering has been considered in Chapter II. Although the simplified speed-time curve discussed in that chapter is convenient for preliminary calculations, it does not correspond to the actual operating conditions. Moreover, an accurate speed-time curve is required for energy calculations.

The calculations for the speed-time curve and the energy consumption are usually carried through together, since certain quantities—e.g. the current and the time—are common to both calculations. However, to simplify matters, we shall at present consider only the calculation of speed-time curves.

For the calculation of the speed-time curve we require—

(1) Complete information of the train service.

(2) A survey of the route, showing the gradients, curves, stations, etc.

(3) Sufficient particulars of the rolling stock and electrical equipment to enable the train resistance to be estimated and the effective weight to be computed.

(4) The characteristic curves of the motors.

The method of calculating the speed-time curve involves only the application of elementary mechanics, the chief feature of the method being the adoption of the speed as the independent variable. The time intervals corresponding to certain increments of the speed are therefore obtained indirectly from the acceleration. The process is essentially a *point-to-point* one, and the accuracy of any point is governed by the accuracy with which the preceding points have been obtained.

The **method of procedure** is best illustrated by working through an example.

Thus, consider that a service of motor-coach trains has to be run at a schedule speed of 16 ml.p.h. over a straight and level track for which the average distance between the stations is 2560 ft.* There is a stop of 20 seconds at each station.

The trains are composed of two motor coaches, weighing 42·5 tons each (without passengers), and four trailer coaches, weighing 22·5 tons each (without passengers), the total seating capacity of a six-coach train being 324. Each coach body has a length of 52 ft., a maximum width of 8 ft. 9 in., and a transverse cross-section of 87·5 sq. ft. The height of the bottom of the side sills above the rails is 2 ft. 11 in. Each coach is mounted on two four-wheel bogie trucks with 36 in. wheels, and each truck of the motor coaches is equipped with two 600-volt direct-current geared motors, the armatures of which are 18 in. in diameter and weigh

* This distance corresponds to the average distance between stations on the "Inner Circle" portion of the Metropolitan District Railway, London.

1500 lb. The gear ratio is 3·5 : 1, and the characteristics of the motors, calculated for this gear ratio, 36-in. wheels, and normal voltage are—

Amperes . . .	50	75	100	150	200	225
Speed (ml.p.h.) . .	36	26·8	22·7	19·5	17·5	16·8
Tractive effort (lb.) .	300	700	1120	2050	3000	3500
Efficiency (per cent) .	70	83	86·6	88·2	87·9	87·5

The mean current input to each motor during rheostatic acceleration is 225 amperes, and the average rate of braking is 2 ml.p.h.p.s.

The **preliminary calculations** which have to be made before the actual calculation of the speed-time curve can be commenced are (1) the effective weight of the train, (2) the train resistances when running with power and coasting, (3) the accelerating tractive effort at various speeds.

The **effective weight** of the train is calculated by the aid of equation (8); the loaded weight of the train (including the 324 passengers) being estimated at 195 tons; and the weight of each wheel being assumed at 900 lb. Thus

$$W_e = 195 + 1{\cdot}2 \times 24 \times \frac{900}{2240} + 0{\cdot}49 \times 8 \times \frac{1500}{2240} \times 3{\cdot}5^2 \times \left(\frac{9}{18}\right)^2$$
$$= 214{\cdot}6 \text{ tons.}$$

The **train resistance** is calculated from equation (38). In the present case the transverse cross-section of the coaches is 78·5 sq. ft., and the motors increase this by about 11·5 sq. ft. Allowing for the chamfered ends of the coaches, the coefficient k in equation (34) may be taken at (0·9(78·5 + 11·5)/78·5 =) 1·05.

Hence the specific train resistance is given by the equation

$$r = 4{\cdot}1 + 0{\cdot}055V + 78{\cdot}5V^2(0{\cdot}0028 \times 1{\cdot}05 + 0{\cdot}0000122 \times 6 \times 52)/195$$
$$= 4{\cdot}1 + 0{\cdot}055V + 0{\cdot}00272V^2$$

the evaluation of which gives the following values for train resistance—

Speed, ml.p.h. (V) .	10	15	20	25	30	35
Specific train resistance, lb. per ton (r) . .	4·92	5·53	6·3	7·2	8·2	9·34

The **apparent train resistance** during coasting will be greater than the above values, on account of the motor friction and gear losses. For the class of equipment under consideration the following values are representative of the friction and gear losses per motor—

Armature speed, r.p.m. . .	250	500	750	1000	1150
Friction and gear loss, kW. .	1·3	3·0	5·1	7·4	8·9

Rearranging these values to correspond to the retarding force per motor, we obtain*—

Speed of train (ml.p.h.).	10	15	20	25	30	35
Retarding force per motor (lb.)	87·5	98	107	114	121	126·5

* The method of converting the loss into retarding force is as follows: With a gear ratio of 3·5 : 1 and 36-in. wheels, the relation between the armature speed (r.p.m.) and the train speed (ml.p.h.) is—

$$\text{ml.p.h.} = (\text{r.p.m.}/3{\cdot}5) \times (60/5280) \times 3\pi = \text{r.p.m.}/32{\cdot}65$$

Hence the retarding force (in lb.) corresponding to the gear and friction losses (in kW.) at this speed

$$= (\text{kW/ml.p.h.}) \times [33000 \times 60/(0{\cdot}746 \times 5280)] = 503 \text{ kW./ml.p.h.}$$
$$= 16440 \text{ kW./r.p.m.}$$

Hence the apparent train resistance during coasting is obtained by adding this additional retarding force to the true train resistance. The steps in the process are shown below—

Speed of train (ml.p.h.) . . .	10	15	20	25	30	35
Specific train resistance (r-lb. per ton)	4·92	5·53	6·3	7·2	8·2	9·34
Total train resistance ($195r$-lb.) .	960	1070	1230	1405	1600	1820
Retarding force due to 8 motors (lb.)	700	784	865	911	967	1010
Total retarding force (lb.) . .	1660	1854	2095	2316	2567	2830
Apparent train resistance (lb. per ton) or retarding force per ton (lb.)	8·5	9·5	10·75	11·88	13·15	14·5

The train resistance and the apparent train resistance during coasting are plotted in Fig. 358.

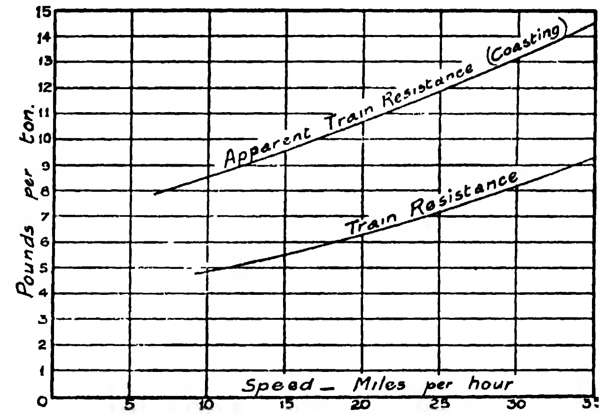


FIG. 358. Train Resistance and apparent Train Resistance of Six-coach, 195-ton Electric Train.

The **tractive effort available for acceleration** at various speeds is readily obtained from the characteristic curves of the motor by deducting the train resistance from the speed tractive-effort curve. Instead of deducting the total train resistance from the total tractive effort of the eight motors, we deduct one-eighth of the total train resistance from the tractive effort of one motor, and thus obtain the accelerating force per motor, as shown in Fig. 359. By considering this force to act upon one-eighth of the mass of the train, we obtain the same conditions as if the total accelerating force of the eight motors acted upon the whole mass of the train.

We have now all the data necessary for the calculation of the speed-time curve.

I. **Period of initial acceleration.** During this period the starting resistance is cut out to maintain the average accelerating current at 225 amperes per motor. When all resistance has been cut out in the parallel combination of the motors, the speed of the train (assuming normal voltage) will be 16·8 ml.p.h. The mean train resistance during this period should not be taken from the above values on account of the rapidly varying speed. An average value of 8 lb. per ton will, therefore, be assumed.

Hence the average tractive effort available for acceleration—

$$= 3500 - \tfrac{1}{8} \times 195 \times 8 = 3500 - 195 = 3305 \text{ lb.}$$

(NOTE.—3500 is the tractive effort corresponding to a current of 225 amperes.)

Therefore, mean acceleration $= 3305/(\tfrac{1}{8} \times 214{\cdot}6 \times 102)$
$= 1{\cdot}21$ ml.p.h.p.s.

Duration of accelerating period $= 16{\cdot}8/1{\cdot}21 = 13{\cdot}9$ seconds.

Distance run during this period $= \tfrac{1}{2} \times 16{\cdot}8 \times 13{\cdot}9 \times 5280/3600$
$= \tfrac{1}{2} \times 16{\cdot}8 \times 13{\cdot}9 \times 1{\cdot}467 = 170$ ft.

II. **Period of speed-curve running.** A series of increments of speed are selected and the mean acceleration for each interval is calculated, after which the time and distance are readily obtained.

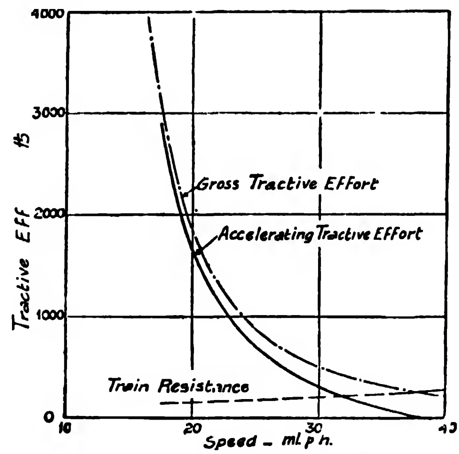


FIG. 359. Curve connecting Speed and Accelerating Tractive Effort per Motor for Six-coach Train.

Thus, consider the increment from 16·8 ml.p.h. to 19 ml.p.h. The mean accelerating tractive effort (from Fig. 359)

$= \tfrac{1}{2}(3305 + 2090) = 2697$ lb.,

and the mean acceleration $= 2697/(26{\cdot}8 \times 102) = 2697/2735$
$= 0{\cdot}987$ ml.p.h.p.s.

Time increment $= (19 - 16{\cdot}8)/0{\cdot}987 = 2{\cdot}23$ seconds

Total time from start $= 13{\cdot}9 + 2{\cdot}23 = 16{\cdot}13$ seconds

Distance run during interval $= \tfrac{1}{2}(16{\cdot}8 + 19) \times 2{\cdot}23 \times 5280/3600$
$= 17{\cdot}9 \times 2{\cdot}23 \times 1{\cdot}467 = 58{\cdot}6$ ft.

Total distance from start $= 171 + 58{\cdot}6 = 229{\cdot}6$ ft.

This process is repeated until the free-running speed (38·5 ml.p.h.) is reached, which speed is obtained directly from Fig. 359.

The results of these calculations are given in Table XIII.

TABLE XIII

Calculation of Speed-time Curve from Start to Free Running for Run on Level Track.

Speed.	Net Tractive-Effort.	Speed Increment.	Mean Accelerating Tractive-Effort.	Mean Acceleration	Time Increment.	Time from Start.	Mean Speed.	Distance Increment.	Total Distance.
ml.p.h.	lb.	ml.p.h.	lb.	ml p.h.p.s.	sec.	sec.	ml.p.h.	ft.	ft.
0	3305					0			0
..	..	16·8	3305	1·21	13·9	..	8·4	171	..
16·8	3305					13·9			171
..	..	2·2	2697	0·987	2·23	..	17·9	58·6	..
19	2090					16·13			230
..	..	2·0	1730	0·633	3·16	..	20	92·7	..
21	1370					19·29			322
..	..	1·5	1210	0·433	3·39	..	21·75	108·1	..
22·5	1050					22·68			430
..	..	2·5	880	0·322	7·76	..	23·75	270	..
25	710					30·44			700
..	..	2·5	600	0·219	11·38	..	26·25	438	..
27·5	490					41·82			1138
..	..	2·5	410	0·15	16·66	..	28 75	702	..
30	330					58·5			1840
..	..	5	218	0·08	62·8	..	32·5	2990	..
35	105					121·3			4830
..	..	3·5	52·5	0·0192	182·2	..	36·75	9810	..
38·5	0					303·5			14640

In the case of short runs, however, we seldom reach free-running speed. It is advisable, therefore, to plot the speed-time and distance-time curves after a few points have been calculated.

Now, for a schedule speed of 16 ml.p.h., the running time for a distance of 2560 ft. is $(2560 \times 3600/(5280 \times 16) - 20 =)$ 89 seconds.

The accelerating and braking portions of the speed-time curve can now be drawn, and are represented in Fig. 360 by OA and DE respectively, OD representing the running time—89 seconds. DE, of course, makes an angle of $(-\tan^{-1} 2)$ with the time axis.

The **points at which the power must be cut off and the brakes applied** must now be determined. We know that the area of the speed-time diagram must represent the distance travelled during the running time—in the present case 2560 ft. Hence the coasting line BC (Fig. 360) must be drawn so that the area $OBCD$ represents 2560 ft., and the inclination of BC to the time axis must correspond to the mean retardation during the coasting period. This process involves trial and error, but with some experience the correct position can usually be obtained on either the first or the second trial.

For instance, suppose we cut off power at 35 seconds when the speed is 26·1 ml.p.h. The distance travelled is then 875 ft., so that the train must coast for a certain period before the brakes are applied. To obtain the duration of the coasting period, a value must be assumed for the

average speed during the coasting period, in order that an appropriate value for the train resistance may be obtained. In the present case the average speed will be assumed as 24 ml.p.h., which corresponds to an apparent train resistance of 11·6 lb. per ton.*

Hence the retardation $= 11{\cdot}6 \times 24{\cdot}35/(102 \times 26{\cdot}8) = 0{\cdot}103$ ml.p.h.p.s. The coasting line BC (Fig. 360) is now drawn on the curve-sheet, and the intersection of this line with the braking line gives us the point at which the brakes must be applied.† This point is found to be at 78·2 seconds, when the speed is 21·6 ml.p.h. Before proceeding further it is necessary

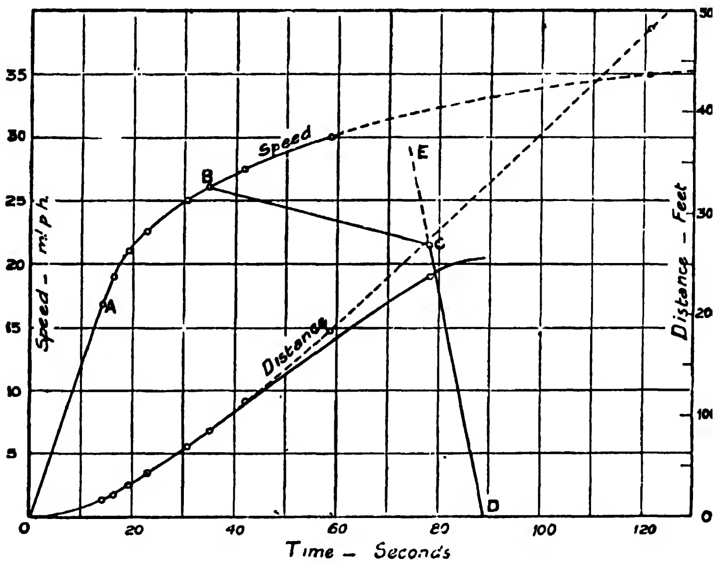


FIG. 360.—Speed-time Curve for Motor-coach Train (2560 ft. run on level track at 16 ml.p.h. schedule speed).

* The mean train resistance during coasting is slightly greater than the train resistance at the mean coasting speed, but the conditions of operation and other variable features do not warrant a closer estimation than that given above.

† The point of application of the brakes may be ascertained analytically by obtaining the co-ordinates of the point of intersection of the coasting and braking lines. Thus the equations of the coasting and braking lines are, respectively, given by

$$V' = U_1 - \beta_c t' \qquad (39)$$

and

$$V'' = U_2 - \beta t'' \qquad (40)$$

where V', V'', denote the speeds at times t', t'' respectively: β_c, β denote the respective retardations during coasting and braking; U_1 and U_2 denote the hypothetical speeds at zero time (i.e. the intercepts on the vertical axis). If V''', t''' denote the co-ordinates of the point of intersection of the coasting and braking lines, then $V''' = U_1 - \beta_c t''' = U_2 - \beta t'''$;

whence

$$t''' = (U_2 - U_1)/(\beta - \beta_c) \qquad (41)$$

V''' is, of course, obtained by substitution.

Applying this method to the above example we obtain the values of U_1 and U_2 by substituting known values for V', V'', t', t''. Thus, at the point of cut-off, $V' = 26{\cdot}1$, $t' = 35$; while at the end of the braking period $V'' = 0$, $t'' = 89$. Hence, adopting the above value for the retardation during coasting, we obtain $U_1 = 26{\cdot}1 + 0{\cdot}103 \times 35 = 29{\cdot}7$; $U_2 = 0 + 2 \times 89 = 178$. Therefore $t''' = (178 - 29{\cdot}7)/(2 - 0{\cdot}103) = 78{\cdot}2$ sec., while $V''' = 178 - 2 \times 78{\cdot}2 = 21{\cdot}6$ ml.p.h.

to check our assumption of the average speed for the coasting period. This is $\frac{1}{2}\{(26{\cdot}1 + 21{\cdot}6) =\}$ 23·85 ml.p.h., so that the value obtained above for the retardation will be substantially correct.

If the area of the diagram $OBCD$ be determined by a planimeter, it will be found to represent 2555 ft., which is sufficiently near the actual distance (2560 ft.) of the run to justify the correctness of our trial.

The alternative method of ascertaining whether or not the point of cut-off has been chosen correctly is to determine the distances by calculation, as follows—

The time of the coasting period	$= 78{\cdot}2 - 35 = 43{\cdot}2$ seconds
and the time of the braking period	$= 89 - 78{\cdot}2 = 10{\cdot}8$ seconds.
Hence the distance run during coasting	$= 23{\cdot}85 \times 43{\cdot}2 \times 1{\cdot}467 = 1510$ ft.
and the distance run during braking	$= \frac{1}{2} \times 21{\cdot}6 \times 10{\cdot}8 \times 1{\cdot}467$
	$= 170$ ft.

The total distance run is, therefore, $875 + 1510 + 170 = 2555$ ft.

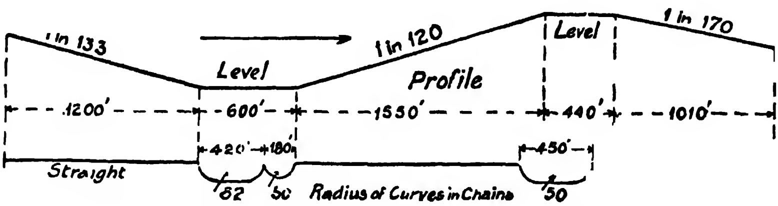


FIG 361.—Profile of Track for Speed-time Curve in Fig. 362.

The complete speed-time curve, together with the distance-time curve, is shown in Fig. 360.

Effect of gradients and curves. In practice we are not generally favoured with ideal track conditions—as assumed in the above example—but we have curves and gradients of varying amounts. When considering the electrification of a particular railway, the energy consumption must be calculated for each section of the route before an accurate value of the average energy consumption over the whole route can be obtained. Hence it will be necessary to determine the speed-time curves for the actual track conditions, and if there are numerous gradients and curves the calculation by the above method will usually consume much time and patience. The effect of the gradients and curves on the train resistance can readily be allowed for, but the time of running on the various gradients and curves must be determined by trial. An example—representing typical conditions on a suburban railway—will best illustrate the method of procedure.

Suppose the above 195-ton motor-coach train has to operate over a section 4800 ft. long at a schedule speed of 20 ml.p.h., with a stop of 20 seconds at the station. The profile of the section is shown in Fig. 361, and the speed-time curve will be calculated for the direction of running indicated by the arrow. The mean accelerating current is 225 amperes (as above), and the average rate of braking *on level track* is 2·0 ml.p.h.p.s.

From an inspection of Fig. 361 it will be apparent that the brakes must be applied when the train is on the falling gradient of 1 in 170. This gradient is equivalent to an accelerating force of $(22{\cdot}4 \times 100/170 =)13{\cdot}2$

lb. per ton of train weight. Hence the actual retardation during braking will equal $(2 - 13{\cdot}2/(1{\cdot}1 \times 102) =)$ 1·88 ml.p.h.p.s.

(NOTE.—1·1 is the ratio of the effective weight of the train (214·6 tons) to the dead weight (195 tons).)

The falling gradient of 1 in 133, on which the train is started, is equivalent to an accelerating force of $(22{\cdot}4 \times 100/133 =)$ 16·8 lb. per ton of train weight, or $(16{\cdot}8 \times \frac{1}{8} \times 195 = 16{\cdot}8 \times 24{\cdot}35 =)$ 410 lb. per motor.

Hence during the initial acceleration (up to a speed of 16·8 ml.p.h.) the mean accelerating tractive effort per motor—on the assumption of 8 lb. per ton for the average train resistance—is $(3500 - 8 \times 24{\cdot}35 + 410 =)$ 3715 lb.

Therefore the mean acceleration $= 3715/(102 \times 26{\cdot}8) = 3715/2735$
$= 1{\cdot}36$ ml.p.h.p.s.

Duration of the period of initial acceleration
$= 16{\cdot}8/1{\cdot}36 = 12{\cdot}35$ seconds.

Distance run during this period $= \frac{1}{2} \times 16{\cdot}8 \times 12{\cdot}35 \times 1{\cdot}467$
$= 152{\cdot}2$ ft.

We now continue the calculation in the same manner (but allow for the effect of the gradient) as in the above example, until a distance of

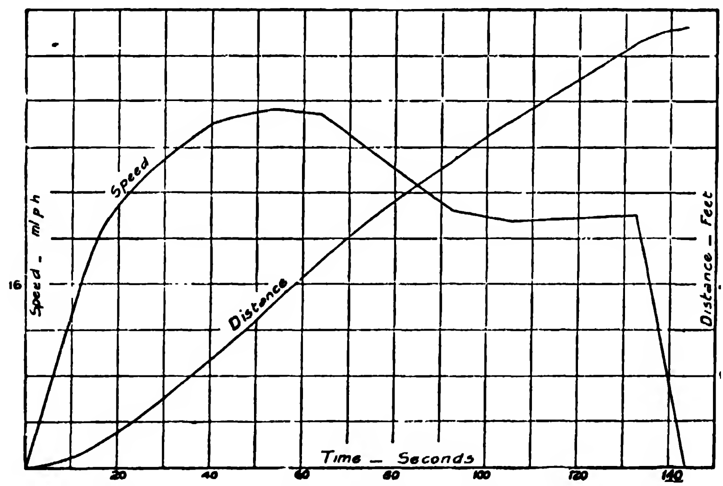


FIG. 362.—Speed-time Curve for Motor-coach Train operating on Track with Curves and Gradients (4800 ft. run at 20 ml.p.h. schedule speed).

1200 ft. has been run. The results of the calculations are given in Table XIV, and it is only necessary to remark that the last increment of speed (for this period) must be obtained by trial.

We have next 600 ft. of level, but curved, track. For the first 420 ft. there is a curve of 62 chains radius $(= 2 \sin^{-1} 50/(62 \times 66) = 1{\cdot}4$ degrees), and for the remainder of the distance there is a curve of 50 chains radius $(= 2 \sin^{-1} 50/(50 \times 66) = 1{\cdot}73$ degrees). These curves increase the train resistance by 1·0 and 1·2 lb. per ton respectively, or an increase in resistance of 24 and 29 lb. respectively per motor.

The accelerating tractive effort is therefore obtained by deducting these values from the appropriate values given in Fig. 359.

A few trials will probably be necessary before the correct distances are obtained.

Next we have to negotiate the rising radient of 1 in 120. This gradient is equivalent to a retarding force of (22·4 × 100/120 =) 18·7 lb. per ton, or (18·7 × 24·35 =) 455 lb. per motor. Hence the mean accelerating (or retarding) tractive effort is obtained by deducting this force—due to the gradient—from the appropriate values given in Fig. 359. Thus, consider the speed decrement 31·43 to 29·5 ml.p.h. The mean accelerating force on level track, obtained from Fig. 359, is {½(250 + 360) =} 305 lb. Hence the net retarding force = 455 - 305 = 150 lb. The retardation is therefore (150/2735 =) 0·055 ml.p.h.p.s.; whence the time and distance follow in the usual manner.

Before making further calculations the speed-time and distance-time curves should be plotted for the purpose of making trials to determine the point of cut-off.

The results of the calculations for the speed-time and distance-time curves up to 89 seconds (i.e. until the second stretch of level track is reached) are given in Table XIV.

TABLE XIV

CALCULATION OF SPEED-TIME CURVE FOR RUN ON TRACK WITH GRADIENTS AND CURVES

Speed.	Net Tractive-effort on level and straight Track.	Tractive-effort due to Gradient or Curve.	Mean Accelerating Tractive-effort.	Speed Increment.	Mean Acceleration.	Time Increment.	Time from Start.	Mean Speed.	Distance Increment.	Total Distance.
ml.p.h.	lb.	lb.	lb.	ml.p.h.	ml.p.h.p.s.	sec.	sec.	ml.p.h.	ft.	ft.
0	3305	+410					0			0
..	..	..	3715	16·8	1·36	12.35	..	8·4	152	..
16·8	3305	+410					12·35			152
..	..	..	3107	2·2	1·135	1·94	..	17·9	51	..
19	2090	+410					14·3			203
..	..	..	2140	2·0	·782	2·66	..	20	75	..
21	1370	+410					16·85			278
..	..	..	1620	1·5	·592	2·53	..	21·75	81	..
22·5	1050	+410					19·4			359
..	..	..	1290	2·5	·472	5·3	..	23·75	185	..
25	710	+410					24·7			544
..	..	..	1010	2·5	·37	6·8	..	26·25	261	..
27·5	490	+410					31·5			805
..	..	+410	810	2·7	·296	9·12	..	28·85	386	..
30·2	310						40·6			1191
..	..	−24	262	0·9	·096	9·4	..	30·65	423	..
31·1	262						50·0			1614
..	..	−29	227	0·33	·083	4·0	..	31·27	184	..
31·43	250						54·0			1798
..	..	−455	−150	−1·93	−·055	35·0	..	30·46	1562	..
29·5	360						89·0			3360

We now make a trial of cutting off power at 64 seconds, when the speed is 30·8 ml.p.h. The distance run during this time is 2257 ft. Consequently the position of the train is 457 ft. up the 1 in 120 gradient. There is, therefore, a further distance of (1550 − 457 =) 1093 ft. to be run up this gradient. The retarding force due to the gradient is 18·7 lb. per ton, and, assuming the mean train resistance to be 12·4 lb. per ton, we obtain the retardation as [(18·7 + 12·4)/(1·1 × 102) =] 0·277 ml.p.h.p.s.

The time required to run the distance of 1093 ft. with this retardation and an initial speed of 30·8 ml.p.h. can be obtained by the application of the general dynamical equation

$$D_1 = V_1 t - \tfrac{1}{2}\beta t^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (42)$$

where V_1 is the initial velocity; β is the retardation, and D_1 is the distance run during the time interval t, all in foot-second units.

In this equation D_1 is given in feet, if V_1 is expressed in feet per second, t in seconds, and β in feet per second per second. For our purpose we require D_1 in feet when V_1 is expressed in ml.p.h. and β is expressed in ml.p.h.p.s. Hence, transforming the equation to these units and solving for t, we obtain

$$t = \{1{\cdot}467V_1 - \sqrt{[(1{\cdot}467V_1)^2 - 2 \times 1{\cdot}467 \times \beta \times D_1]}\}/1{\cdot}467\beta \qquad (43)$$

Inserting the above values for V_1, D_1, and β, we obtain $t = 28{\cdot}4$ sec.

The speed decrement for this interval is (28·4 × 0·277 =) 7·85 ml.p.h. Hence the speed at the end of the interval is (30·8 − 7·85 =) 22·94 ml.p.h., and the mean speed is 26·87 ml.p.h. The train resistance corresponding to the mean speed is 12·4 lb. per ton (from Fig. 358), so that the assumption of 12·4 lb. per ton is correct, although, in the present instance, an error of 1 lb. per ton would have affected the retardation by only 3 per cent.

The run along the level stretch of 440 ft. is next calculated, and we finally reach the falling gradient of 1 in 170 on which the train is to be brought to rest. The train commences the descent of this gradient at a speed of 21·47 ml.p.h., the time being 105·8 seconds. The gradient produces an accelerating force of 13·2 lb. per ton, and if the mean train resistance is assumed to be 11·1 lb. per ton, we have a net accelerating force, due to the gradient, of (13·2 − 11·1 =) 2·1 lb. per ton, which produces an acceleration of 0·0187 ml.p.h.p.s.

Now the running time = 4800/(20 × 1·467) − 20 = 143·5 sec.

Hence the time on this (1 in 170) gradient = 143·5 − 105·8 = 37·7 sec., which includes the time for braking.

The point at which the brakes must be applied may be determined either from the curve sheet or by a few trial calculations: it will be found to be at 132·4 sec., when the speed is 21·97 ml.p.h.

Hence the duration of the braking period is 11·1 sec., and the time of coasting down the gradient is 26·6 sec.

Therefore the distance run during braking is

$$(\tfrac{1}{2} \times 21{\cdot}97 \times 11{\cdot}1 \times 1{\cdot}467 =)\ 179 \text{ ft.},$$

and the coasting distance is

$$\{\tfrac{1}{2}(21{\cdot}47 + 21{\cdot}97) \times 26{\cdot}6 \times 1{\cdot}467 =\}\ 848 \text{ ft.}$$

Summing up the various distances, we obtain a total of 4817 ft.

The complete speed-time and distance-time curves are given in Fig. 362, while the results of the calculations for the coasting and braking periods are given in Table XV.

TABLE XV

CALCULATION OF COASTING AND BRAKING PORTION OF SPEED-TIME CURVE FOR RUN ON TRACK WITH GRADIENTS AND CURVES

Speed.	Mean Train Resistance.	Retarding Force due to Gradient or Curve.	Mean Retarding Force.	Mean Retardation.	Time Increment.	Speed Decrement.	Distance Increment.	Mean Speed.	Time from Start.	Total Distance from Start.
ml.p.h.	lb. per ton.	lb. per ton.	lb. per ton.	ml.p h.p.s.	sec.	ml p h.	ft.	ml.p.h.	sec.	ft.
30·8	..	..	..	..	..	..	..	..	64	2259
	12·4	18·7	31·1	·277	28·4	7·85	1093	26·87		
22·94	..	..	..	..	..	..	..	..	92·4	3350
	11·1	1·2	12·4	·11	13·4	1·47	440	22·2		
21·47	..	..	..	..	..	..	..	..	105·8	3790
	11·1	−13·2	−2·1	−·0187	26·6	−·05	848	21·72		
21·97	..	..	..	..	..	..	..	..	132·4	4638
				1·88	11·1	21·97	179	10·98		
0	..	..	..	..	..	..	..	..	143·5	4817

In cases where speed-time curves are required for runs extending over many gradients, the calculations can be carried out more expeditiously by adopting the analytical method developed by Dr. F. W. Carter, and described in detail in a paper entitled "Predetermination in Railway Work."* In this method the treatment of problems connected with train movement is based upon the assumption that, within the working range of ordinary direct-current series traction motors, the relations between the tractive effort and the current may be represented by a straight line, while the relation between the speed and the current may be represented by a hyperbola. From these premises a series of equations connecting the speed, distance, tractive effort, and time are developed, and a set of universal speed-time and speed-distance curves are obtained from which those appropriate to the problem can be selected.

PART II—ENERGY CONSUMPTION (DIRECT-CURRENT EQUIPMENTS)

One of the characteristic features of electrical engineering is that the energy input to a motor, or a group of motors, performing a definite cycle of operations can be predetermined with a high degree of accuracy when the characteristic curves of the machines are available and the mechanical resistances are known. This feature also applies to electric

* See *Transactions of the American Institute of Electrical Engineers*, vol. 22, p. 133. This paper should be studied by all students interested in the subjects of speed-time curves and energy consumption. Further papers on speed-time curves will be found in vol. 19, pp. 129, 901; vol. 33, p. 1673.

railway engineering. For instance, the performance of a given electric train, operating to a given schedule in suburban service, can be predetermined with precision, since the uncertain factors (such as train resistance) connected with the problem influence the final results to only a small degree. Hence, in making guarantees for the energy consumption of suburban electric trains it is only necessary to add a small allowance (to cover unforeseen contingencies) to the calculated figures; in fact, this allowance is, in many cases, only of the order of 5 per cent. It is now our purpose to show the manner in which these calculations are made.

In order to calculate the energy required by an electric train when operating to a given schedule, it is necessary to have available the speed-time curve corresponding to the conditions of service and the characteristic curves of the driving motors, while a knowledge of the method of control will also be necessary.

In principle, the **method of calculation** is similar to that adopted for the calculation of the speed-time curve, i.e. the speed is considered as the independent variable, and the increments in the time and current, corresponding to increments in the speed, are obtained. The increments in the energy are then calculated, and the total energy supplied follows by a process of summation.*

Example. The method of procedure is best illustrated by calculating the energy consumption for the 2560 ft. run for which the speed-time curve was calculated in the earlier part of this chapter.

In the calculations which follow, the energy supplied to one motor is calculated, and the total energy supplied to the train is obtained by multiplying by the number of motors. This method possesses an advantage over the direct method of calculating the total energy, since the standard characteristic curves of the motor can be used without modification.

The characteristics of the motors with which the train under consideration is equipped are given on p. 506. Of these characteristics, we only require the speed-current curve for the energy calculations, but we shall utilize the efficiency curve later in order to obtain the average efficiency during the period of speed-curve running.

I. **Period of rheostatic acceleration** (i.e. from the start until a speed of 16·8 ml.p.h. is reached). During this period the current per motor will be assumed to be maintained constant at 225 amperes.† With series-parallel control, the input (from the conductor rails) to a pair of motors during the first half of this period (when the motors are in series) will be $225 \times 600 = 135$ kW., and during the second half of the period (when the motors are in parallel) the input will be $2 \times 225 \times 600 = 270$ kW. Hence the energy input per motor for the whole of the initial accelerating

* The total energy supplied may also be obtained by plotting a power-time curve and integrating this by means of a planimeter.

† In practice, with a limited number of controller notches the current will fluctuate between maximum and minimum values as the sections of the rheostats are cut out. With suitably graded rheostats and the controller manipulated to give uniform current-peaks (e.g. as is obtained with automatic control), the deviation of the actual conditions from the ideal will not introduce any appreciable errors into the calculation of either the speed or the energy consumption.

period will be* $\{\frac{1}{2}(135 \times \frac{1}{2} \times 13{\cdot}9 + 270 \times \frac{1}{2} \times 13{\cdot}9) =\}$ 1409 kW.-seconds, or $(1409 \times 1000/3600 =)$ 391 watt-hours.

II. **Period of speed-curve running.** The energy input during this period is obtained by selecting a series of increments of the speed, calculating the average energy input for each increment, and summing the results.

Thus the interval from 16·8 ml.p.h. to 19 ml.p.h. occupies 2·23 sec., and the average current is $\{\frac{1}{2}(225 + 160) =\}$ 192 amperes, so that the average energy input $= (192 \times 600 \times 2{\cdot}23)/3600 = 71{\cdot}4$ watt-hours.

Similarly, for the intervals until cut-off, we obtain the following results:—

Speed Increment (ml p h).	Time Interval (seconds).	Average Current (amperes).	Average Energy Input. (watt-hours).
19 to 21	3·16	141	74·2
21 to 22·5	3·29	114	64·4
22·5 to 25	7·76	93	120
25 to 26·1	4·6	83·5	64

The average energy input per motor for the whole run is, therefore, $(391 + 71{\cdot}4 + 74{\cdot}2 + 64{\cdot}4 + 120 + 64 =)$ 785 watt-hours. Hence the total energy consumption for the train is $(785 \times 8/1000 =)$ 6·28 kW.-hours, or $(6{\cdot}28 \times 5280/2560 =)$ 12·95 kW.-hours per train mile.

The specific energy consumption $= 12{\cdot}95 \times 1000/195 = 66{\cdot}4$ watt-hours per ton mile.

Analysis of energy consumption. It is instructive to analyse this energy consumption into its several components. Thus—

Energy expended during braking† $= \dfrac{0{\cdot}0283 \times (21{\cdot}6)^2 \times 214{\cdot}6 \times 5280}{2560 \times 195}$

$=$ 29·9 watt-hours per ton mile

Energy expended against train resistance (while power is on)‡ . 4·7 watt-hours per ton mile

Energy expended against apparent train resistance during coasting (difference between kinetic energy at 26·1 ml.p.h. and 21·6 ml.p.h.) . 13·8 watt-hours per ton mile

* The series and parallel portions of the initial accelerating period are here considered to be of equal duration. A reference to Fig. 106 (p. 168) will show that, due to the internal resistance of the motors, the time of running on the series notches is slightly shorter than that for the parallel notches when the accelerating current per motor is maintained constant. In the present case, assuming a 5 per cent voltage drop in each motor, the respective times on the series and parallel notches are 6·58 and 7·32 seconds, so that the energy input per motor during the initial accelerating period is 1432 kW. seconds instead of 1409. The specific energy consumption, however, only differs 0·5 per cent in the two cases.

† Obtained from equation (10). See p. 30.

‡ Obtained as follows. Average train resistance between 16·8 ml.p.h. and 26·1 ml.p.h. = 6·6 lb. per ton. Total distance up to the point of cut-off is 875 ft., whence from equation (11), p. 32, energy expended against train resistance (while power is on) $= (2 \times 8 \times 170/2560) + (2 \times 6{\cdot}6 \times (875 - 170)/2560) = 4{\cdot}7$ watt-hours per ton mile.

Losses in starting rheostats* = 10·5 watt-hours per ton mile
Losses in motors and gearing (by difference) = 7·5 watt-hours per ton mile

The energy utilized during the run = 4·7 + 13·8 = 18·5 watt-hours per ton mile, or 28 per cent of the energy supplied from the conductor rails. The remaining 72 per cent is accounted for as follows: 45 per cent is dissipated in the brake shoes, 12 per cent is dissipated in the starting rheostats, and 12 per cent is dissipated in the motors and gearing.

Of the kinetic energy possessed by the train at the point of cut-off, 31·6 per cent is utilized during coasting, and the remaining 68·4 per cent is dissipated in the brake shoes.

Although the schedule speed is fairly high for such a short run, the energy consumption is not excessive. This result is due to the adoption of moderately high acceleration and retardation, by which means a long coasting period is obtained (e.g. the duration of coasting period is 48·5 per cent of the running period).

Effect of acceleration and rate of braking on energy consumption. We will investigate the effect of, say, a 17·5 per cent reduction in the initial acceleration for the above service, the schedule speed, rate of braking, and other conditions remaining unchanged.

The mean tractive effort per motor to give an acceleration of 1·0 ml.p.h.p.s. (allowing 8 lb. per ton for train resistance) is $(1{\cdot}0 \times 102 \times 26{\cdot}8 + 8 \times \frac{1}{8} \times 195 =)$ 2928 lb., which corresponds to a current of 195 amperes. The speed of the train, corresponding to this current and normal voltage, is 17·6 ml.p.h. Hence the duration of the initial accelerating period = 17·6/1·0 = 17·6 seconds.

The average energy input (per motor) during the initial accelerating period $= \frac{1}{2}(195 \times 600 \times \frac{1}{2} \times 17{\cdot}6 + 2 \times 195 \times 600 \times \frac{1}{2} \times 17{\cdot}6)/3600 =$ 429 watt-hours. By calculating the speed-time curve in the manner indicated above, we find that power must be cut off at 41 seconds when the speed is 26·8 ml.p.h., and the brakes must be applied at 77·5 sec. when the speed is 23 ml.p.h. The energy input (per motor) for the whole run is 840 watt-hours, or 7 per cent greater than that for the higher acceleration. The duration of the coasting period in the present instance is 41 per cent of the running period.

* Obtained as follows: Assuming a 5 per cent voltage drop in each motor and a constant supply voltage of 600 volts, the times on the series and parallel notches are, respectively, 6·58 and 7·32 seconds. The mean voltage drop in the rheostats during series notching is $[\frac{1}{2}\{600(1 - 2 \times 0{\cdot}05)\} =]$ 270 volts, while the value corresponding to the parallel notches is 150 volts. Hence the energy dissipated in the rheostats (per pair of motors) is $[(225 \times 270 \times 6{\cdot}58 + 2 \times 225 \times 150 \times 7{\cdot}32)/3600 =]$ 248 watt-hours, which corresponds to $248 \times 4 \times 5280/(195 \times 2560) = 10{\cdot}5$ watt-hours per ton mile. If the internal resistance of the motors is neglected, the loss in the rheostats will be given by $\frac{1}{2}$ (kinetic energy of train at end of initial accelerating period + work done against train resistance). Applying this rule to the above example, we have—

Kinetic energy of train at 16·8 ml.p.h. $= (0{\cdot}0283 \times (16{\cdot}8)^2 \times 214{\cdot}6 \times 5280)/(2560 \times 195) = 18{\cdot}1$ watt-hours per ton mile.

Work done against train resistance $= 2 \times 8 \times 170/2560 = 3{\cdot}36$ watt-hours per ton mile.

Therefore the approximate loss in rheostats $= \frac{1}{2}(18{\cdot}1 + 3{\cdot}36) = 10{\cdot}73$ watt-hours per ton mile.

The **energy account** for this run is as follows—

Energy dissipated in the brake shoes	= 33·9 watt-hours per ton mile
Energy expended against train resistance (while power is on)	= 6·8 watt-hours per ton mile
Energy expended against (apparent) train resistance during coasting	= 12·1 watt-hours per ton mile
Losses in starting rheostats	= 11·5 watt-hours per ton mile
Losses in motors and gearing	= 6·8 watt-hours per ton mile

The lower acceleration, however, will result in a *lower maximum output per motor* and a lower maximum load on the sub-station. Thus, in the first case, the maximum output per motor, calculated from equation (9), $= 0{\cdot}002 \times 3500 \times 16{\cdot}8 = 156$ h.p.; and in the second case, this becomes $0{\cdot}002 \times 2928 \times 17{\cdot}6 = 137{\cdot}5$. Similarly, the *maximum input* to the train is, in the first case, $(225 \times 600 \times 8/1000 =)$1080 kW.; and, in the second case, $(195 \times 600 \times 8/1000 =)$ 936 kW., which is 13·4 per cent lower than the former.

It will be interesting to ascertain the difference in the **heating of the motors** in the two cases. Although the heating is due to core, friction, and I^2R losses, we shall only consider the I^2R losses, since the other losses will not differ materially in the two cases. Hence the heating may be considered as proportional to the root-mean-square (r.m.s.) current for the cycle (i.e. from start to start).

The current-time curves (for one motor) are given in Fig. 363. By converting the current-time curve into a (current)^2-time curve, and integrating the latter over the period from start to start, we can obtain the r.m.s. value of the current for the cycle. Thus, for the first run, the mean square of the current, over the period from start to start, = 991,850/109 = 9100. Therefore the r.m.s. current = 95·4 amperes.

For the second run, the mean square of the current, over the period from start to start = 944,600/109 = 8670. Therefore the r.m.s. current = 93·1 amperes.

The heating of the motors will, therefore, be only slightly reduced by adopting the lower acceleration, and practically the same size of motor will be required in each case.

The comparisons between the two runs may be summarized thus—

Initial acceleration (ml.p.h.p.s.)	1·21	1·0
Rate of braking (ml.p.h.p.s.)	2·0	2·0
Initial accelerating current per motor (amp.)	225	195
R.m.s. current per motor (amp.)	95·4	93·1
Specific energy consumption (Wh. per ton mile)	66·4	71·1
Total energy consumption(kW.h.)	12·95	13·9
Maximum input from conductor rails (kW.)	1080	936
Average input from conductor rails (kW.)	202	222
Maximum output from motors (h.p.)	1250	1100
Maximum speed (ml.p.h.)	26·1	26·8
Speed at commencement of braking (ml.p.h.)	21·6	23
Time from start to point of cut-off (sec.)	35	41
Duration of coasting period (sec.)	43·2	36·5
Duration of braking period (sec.)	10·8	11·5
Energy utilized (Wh. per ton mile)	18·5	18·9
Energy dissipated in brakes (Wh. per ton mile)	29·9	33·9
Energy dissipated in starting rheostats (Wh. per ton mile)	10·5	11·5
Energy dissipated in motors and gears (Wh. per ton mile)	7·5	6·8

It is apparent that, from the energy point of view, the adoption of the higher acceleration has considerable advantages. The disadvantages are: (1) a higher peak load on the sub-stations, (2) a slightly increased maintenance on the rolling stock and equipment. Of course, if the acceleration were increased to, say, 1·5 ml.p.h.p.s., larger equipments would be necessary, and in this case it is quite possible that, although the specific energy consumption would be reduced, the total energy consumption may be increased. Moreover, this high acceleration would increase considerably the peak load on the sub-station, thereby necessitating more expensive plant and larger feeders.

The **influence of the rate of braking on the energy consumption** is shown by the following figures, which have been calculated for the above

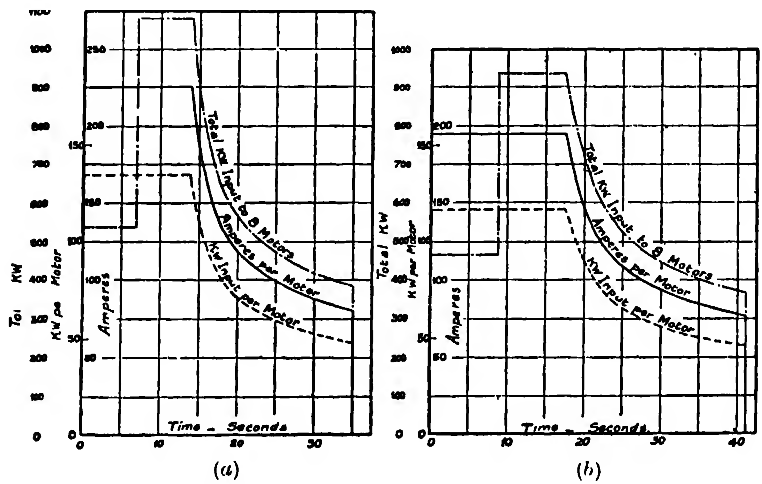


FIG. 363.—Current and Power Curves for 195-ton Motor-coach Train. (a) Accelerating current = 225 A. per motor; (b) Accelerating current = 195 A. per motor.

train. The initial acceleration has been chosen at 1·21 ml.p.h.p.s., so that the results can readily be compared with those obtained previously, and which are given below for comparison.

Average rate of braking (ml.p.h.p.s.)	2·0	2·75	1·5
Initial acceleration (ml.p.h.p.s.)	1·21	1·21	1·21
Time at which power is cut off (sec.)	35	33	43
Time at which brakes are applied (sec.)	78·2	81·6	69·5
Maximum speed (ml.p.h.)	26·1	25·6	27·6
Speed at commencement of braking (ml.p.h.)	21·6	20·3	24·5
Duration of coasting period (sec.)	43 2	48·6	26·5
Duration of braking period (sec.)	10·8	7·4	19·5
Specific energy consumption (Wh. per ton mile)	66·4	64	75·3
Energy dissipated in brakes (Wh. per ton mile)	29·9	26·4	38·5

Thus, considering the rate of braking to be normally 2·0 ml.p.h.p.s. a reduction of 25 per cent increases the energy consumption by 13 per cent; and an increase of 37·5 per cent reduces the energy consumption by 4 per cent.

The relationship between the rate of braking and the energy consumption is shown better in Fig. 364, which is plotted from the above results. It is apparent, therefore, that for the above service very little advantage is gained by the adoption of a braking rate above 2·0 ml.p.h.p.s.

Influence of length of run on energy consumption. Fig. 365* is plotted from test results of the energy consumption for a number of runs with 175-ton motor-coach trains when operating at constant schedule speed. As the runs were all made with the same driver, the effect of the personal element on the performance is practically the same for each run.

Effect of gear ratio and method of control on energy consumption. Since the energy consumption of a train operating to a given schedule is influenced by the duration of the coasting period, it is clear that any conditions of operation which will increase the coasting period will result in reduced energy consumption.† When the length of the run, the schedule

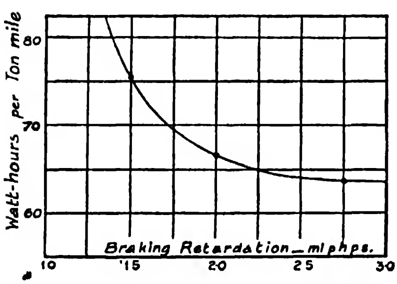


FIG. 364.– Effect of Rate of Braking on Specific Energy Consumption (2560 ft. run at 16 ml.p.h. schedule speed; acceleration - 1·21 ml.p.h.p.s.).

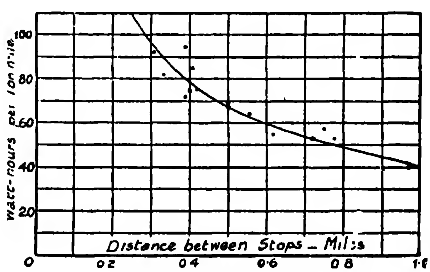


FIG. 365. Influence of Length of Run on Specific Energy Consumption (weight of train 175 tons; schedule speed 17 ml.p.h.).

speed, and the rate of braking are fixed, the coasting period will be affected only by (1) the initial acceleration, and (2) the free-running speed. With short runs the initial acceleration will have the greater influence on the energy consumption, but with longer runs the energy consumption will be largely dependent on the free-running speed.

Now, if with a given equipment the gear-ratio be changed, the initial acceleration and the free-running speed will be changed; consequently the saving resulting from, say, a higher initial acceleration will be offset by the longer duration of the speed-curve running period, due to the lower free-running speed (assuming the schedule speed to be unaffected by the change). Whether or not the energy consumption will be affected by the change of gearing will depend upon the relative values of the energy consumption for the accelerating and speed-curve running periods in each case, and a definite decision can only be arrived at by working through the speed-time curves and calculating the energy consumption in the usual manner.

* From a paper by Mr. Roger T. Smith on "Some Railway Conditions Governing Electrification" (*Journal of the Institution of Electrical Engineers*, vol. 52, p. 293).

† This statement assumes that the increased coasting is obtained by altering either the initial acceleration or the braking, or both; the acceleration on the speed-curve being unaltered. In other words, the gear ratio is assumed to remain constant.

In order to illustrate this point, we show, in Fig. 367, speed-time curves—for the above 195-ton motor-coach train—corresponding to gear ratios of 2·5: 1, 3·5: 1, and 4·5: 1, the schedule speed, distance of run, rate of braking, and accelerating current being the same in each case. The energy consumption has also been calculated, and the values are given in Table XVII.

Before giving these results, it will be desirable to indicate the modifications required to the above data to allow for the change of gear ratio.

The characteristics of the motors (p. 506) are modified in the following manner. If V denotes the speed corresponding to a given current and gear ratio γ, then for a gear ratio γ_1, the speed (V_1) at the same current is given by $V_1 = V\gamma/\gamma_1$. Again, if F, F_1 denote the tractive efforts corresponding to a given current, then $F_1 = F\gamma_1/\gamma$.*

The modified values of the speed and tractive effort are as follow—

Current (amperes) . . .	225	175	125	100	75	50
Speed, 2·5 : 1 gear ; 36 in. wheels (ml.p.h.)	23·5	25·6	29·3	32·5	38·1	51·4
Speed, 4·5 : 1 gear ; 36 in. wheels (ml.p.h.)	13·07	14·25	16·25	18	21·2	28·6
Tractive effort, 2·5 : 1 gear ; 36 in. wheels (lb.)	2500	1800	1130	805	500	214
Tractive effort, 4·5 : 1 gear ; 36 in. wheels (lb.)	4500	3240	2030	1405	900	385

The change in the gear ratio will affect the apparent train resistance during coasting. The values on p. 507 and Fig. 358 must, therefore, be modified to correspond to the change in the gearing, the modification being effected by the method given in the footnote on p. 506. The results of these modifications are as follows—

Speed of train (ml.p.h.) .	10	15	20	25	30	35	40
Apparent train resistance for gear ratio 2·5 : 1 lb. (per ton) . . .	7·6	8·16	9·13	10·25	11·45	12·7	14·1
Apparent train resistance for gear ratio 4·5 : 1 (lb. per ton) . . .	10	11·1	12·4	13·7	15·1	—	—

The effective weight of the train will also be affected by the change in the gear ratio due to the change in the ratio of the speed of the train to the speed of the armatures. By the application of equation (8), p. 29, the effective weight is found to be 210·6 tons when the gear ratio is 2·5: 1, and 217 tons when the gear ratio is 4·5: 1.

Hence, for an accelerating current of 225 amperes per motor and a gear ratio of 2·5: 1, the initial acceleration is

$$[(2500 - 195)/(\tfrac{1}{8} \times 210{\cdot}6 \times 102) =]\ 0{\cdot}86 \text{ ml.p.h.p.s.}$$

With a gear ratio of 4·5: 1 the initial acceleration is

$$[(4500 - 195)/(\tfrac{1}{8} \times 217 \times 102) =]\ 1{\cdot}55 \text{ ml.p.h p.s.}$$

* This assumes that the gear and axle-friction losses are the same in each case, which assumption may be considered to be approximately correct, since, although the speeds of the axle and gearing (corresponding to a given speed of the armature) are increased with a reduction in the gear ratio, the tooth and bearing pressures are reduced.

TABLE XVI

SUMMARY OF THE RESULTS OF CALCULATIONS FOR A 195-TON MOTOR-COACH TRAIN OPERATING AT A SCHEDULE SPEED OF 16 ML.P.H. ON A RUN OF 2560 FT. ON LEVEL TRACK, WITH STOPS OF 20 SECONDS DURATION.

Gear ratio	2·5	3·5	4·5
Initial accelerating current per motor (amp.)	225	225	225
Rate of braking (ml.p.h.p.s.)	2·0	2·0	2·0
Initial acceleration (ml.p.h.p.s.)	0·86	1·21	1·55
Specific energy consumption (Wh. per ton mile)	84	66·4	64
Maximum input from conductor rails (kW.)	1080	1080	1080
Average input from conductor rails (kW.)	262	202	200
Maximum output from motors (h.p.)	156	156	156
Free-running of speed train (ml.p.h.)	43·5	38·5	32·5
Maximum speed of train during run (ml.p.h.)	28	26·1	25·5
Speed of train when rheostats are cut out (ml.p.h.	23·5	16·8	13·1
Speed of train at commencement of braking (ml.p.h.)	24	21·6	21·8
Mean retardation during coasting (ml.p.h.p.s.)	0·096	0·103	0·117
Time from start to point of cut off (sec.)	35	35	46·5
Duration of coasting period (sec.)	42	43·2	31·6
Duration of braking period (sec.)	12	10·8	10·9
Energy utilized (Wh. per ton mile)	18	18·5	17·5
Energy dissipated in brakes (Wh. per ton mile)	36·9	29·9	30·5
Energy dissipated in starting rheostats (Wh. per ton mile)	20·6	10·5	6·4
Energy dissipated in motors and gears (Wh. per ton mile)	8·5	7·5	9·6
R.m.s. current per motor (amp.)	121·5	95·4	80·8
Peripheral speed of gearing at free-running speed (ft. per min.)	2260	2260	2000
Diameter of pitch circle of gear wheel (in.).	22·5	24·5	25·8

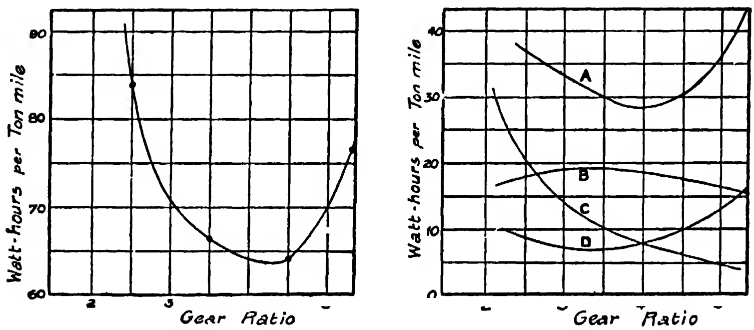
The **relationship between the energy consumption and the gear ratio** for the above conditions of operation is shown in Fig. 366 (*a*). We observe that the energy consumption is not materially affected by changes in the gear ratio between 3·75: 1 and 4·5: 1, but is increased considerably for gear ratios below 3·0: 1 and above 4·5: 1. For example, for a gear ratio of 5·3: 1 (which is the highest gear ratio with which the service can be run, power being kept on for 76 seconds, and the brakes applied immediately power is cut off), the energy consumption reaches 78·6 watt-hours per ton mile.

In the above considerations of the effect of the gear ratio on the energy consumption we have neglected the mechanical limitations, such as (1) the clearance between the lowest point of the gear case and the track, and (2) the peripheral speed of the gearing. These limitations are discussed in Chapter XVII (p. 437), and must be carefully considered, as well as the energy consumption, in the selection of a suitable gear ratio for a given equipment.

The comparison between the above runs is greatly facilitated by plotting the values of the energy expended in the various parts of the equipment against the gear ratio, as shown in Fig. 366 (*b*). We have now an explanation of the rapid rise in the energy consumption when the gear ratio is increased above 4·5: 1; for, although the energy

dissipated in the rheostats is reduced, the energy dissipated in the motors and gearing, as well as in the brakes, is increased.

The increased losses in the motors are principally friction losses, consequent upon the high armature speed. For instance, in the particular motor for which the characteristics are given on p. 506, the friction and (gear) losses at an armature speed of 1200 r.p.m. (corresponding to a train speed of 26 ml.p.h. with a gear ratio of 5·3: 1) are approximately 20 per cent of the input to the motor. With a high gear ratio, a large portion of the run must be made at speeds in the neighbourhood of free running, and as this condition usually corresponds to a high armature speed, the average equipment efficiency during this period is low. This point is clearly shown by the curves of Fig. 367, which refer to the above runs, with an additional curve for the maximum gear ratio (5·3: 1) added.* Comparing the runs with gear ratios of 3·5: 1 and 5·3: 1,



(a) (b)

FIG. 366. Effect of Gear Ratio on Energy Consumption of 195-ton Motor-coach Train (2560 ft. run at 16 ml.p.h. schedule speed). (a) Energy Consumption; (b) Components of Energy Consumption. A. Energy dissipated in brake shoes. B. Energy expended against train resistance. C. Energy dissipated in rheostats. D. Energy dissipated in motors and gearing.]

the mean efficiencies during the periods of speed-curve running are 86·8 per cent and 73·4 per cent respectively.

The curves of Fig. 367 also indicate the **ideal conditions for obtaining a low energy consumption** with the standard method of series-parallel control. Thus, suppose it were possible to adopt the 5·3: 1 gear for the initial accelerating period, and to change this gear to 3·5: 1 at a speed of 17·25 ml.p.h. (corresponding to the intersection of the speed-time curves for these gear ratios). We should then be able to cut off power earlier (e.g. at 30 seconds), to coast longer, and to apply the brakes at a lower speed than if we made the run with the 3·5: 1 gear throughout. The specific energy consumption for this method of operation is 57·6 watt-hours per ton mile, of which 27 watt-hours per ton mile are expended in the brakes.

* The points for the portion of the efficiency curve corresponding to speed-curve running are obtained directly from the motor efficiency curve (p. 506), while the points for the portion corresponding to the initial acceleration are obtained from the ratio of the output to the input, the output being (kinetic energy of train + work done against train resistance).

Of course, such a method of operation is quite impracticable, but with motors designed for "tap-field" control, we can obtain conditions somewhat similar to the above. Thus, at starting, the full field winding would be used, thereby giving a low speed at which the rheostats are cut out, while for the speed-curve running period the field tappings would be used, thereby enabling this portion of the run to be made at a moderately high speed, so as to obtain a long coasting period.

Energy consumption of equipments operating on various services. In the above discussion we have considered conditions of service which

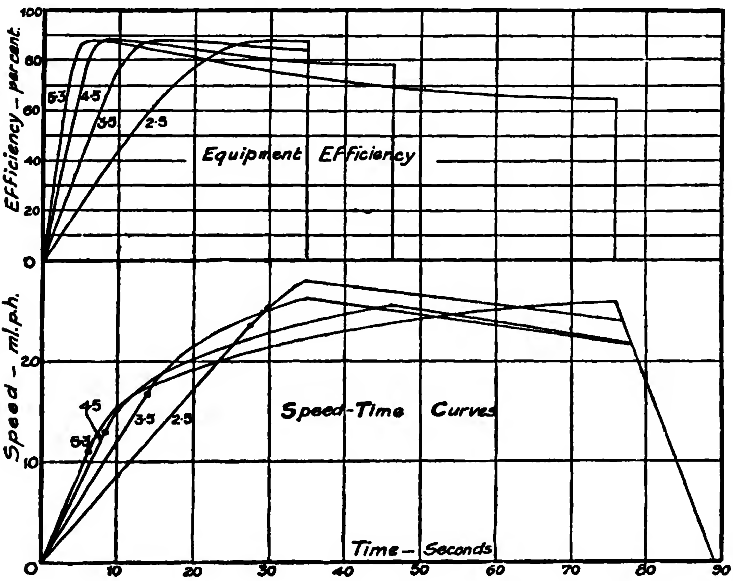


FIG. 367.—Speed-time and Equipment-efficiency Curves for Motor-coach Train (2560 ft. run at 16 ml.p.h. schedule speed). NOTE—The numbers placed against the curves denote the gear ratio. The points marked • indicate the commencement of the speed-curve running periods.

are typical for city lines. But, with an extensive system of electrification—involving the electrification of city, suburban, and interurban lines—the traffic department would require the suburban and interurban trains to be scheduled for a faster service than the city trains. Hence, if the same trains are operated over both city and interurban routes, the gear ratio cannot be selected to give the most economical operation on each system. For instance, suppose the average run of 5000 ft. is to be made at a schedule speed of 24·5 ml.p.h., with stops of 20 seconds' duration. The running time is 119 seconds. A reference to p. 510 will show that the above equipment, with a gear ratio of 3·5 : 1 and 36 in. wheels, is quite incapable of operating to this schedule. A lower gear ratio (between 2·0 : 1 and 2·5 : 1) must, therefore, be employed; and to avoid an excessive gear velocity at free-running speed (which in this case would be of the order of 45 to 50 ml.p.h.), the diameter of the driving wheels require to be increased to 43·5 in. A reference to Fig. 366 (*a*) will

show that such an equipment would have a high energy consumption when operating on the city service.

Moreover, if a compromise in the gear ratio be adopted, the energy consumption for the suburban and interurban services will be higher than that of a train equipped with the correct gear ratio for these services.

These disadvantages are to some extent minimized by employing **equipments with tapped field control.** For example, if the motors are provided with two tappings on each field spool, three field strengths are

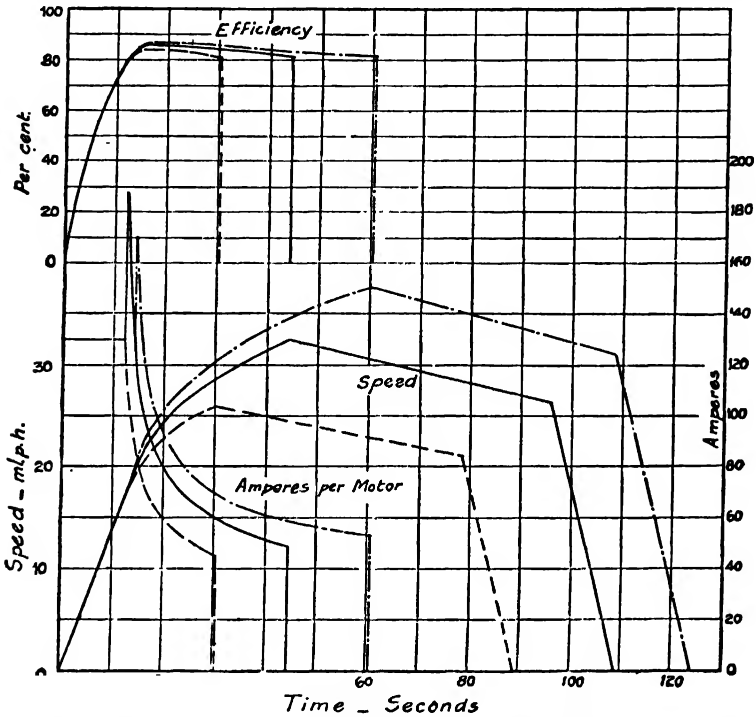


FIG. 368.—Speed, Current, and Efficiency Curves for Motor-coach Train with Field-control Equipment.
- - - - Full field. —— - —— Normal field. —.—.— Minimum field.

obtained with a given value of the armature current. The full field winding would then be used for the initial acceleration in each of the above services, and the tappings would be used for obtaining the higher speeds required for the suburban and interurban routes. The gear ratio would be selected to give a moderately high acceleration, so that the train could be operated economically in city service.

Field control, therefore, *considerably extends the flexibility of the equipment*, and, with a suitable selection of the motor, *one class of equipment will be capable of operating on widely different services without the energy consumption, on any of the services, being excessive.* This feature of field-control equipments can be better illustrated by an example.

Thus, consider a train of two 36-ton motor coaches, with equipments arranged for tapped-field control, to operate on level track to various

schedules, the braking retardation being 2 ml.p.h.p.s. in all cases. The coach bodies are of the same dimensions as those in the above examples. The trucks have 43½ in. wheels, and each truck is equipped with two 75 h.p., 500-volt, geared motors, the gear ratio being 3·9: 1. The weight of the train loaded with passengers is 79 tons, and the effective weight is 86·5 tons.

The characteristics of the motors at normal voltage and for 43½ in. wheels, 3·9: 1 gear ratio, are as follow—

Amperes	40	60	80	100	130
Speed, full field* (ml.p.h.)	27·5	22·5	20	18·4	17
Speed, normal field* (ml.p.h.)	38	28·7	24	21·6	19·5
Speed, weak field* (ml.p.h.)	50	33·7	27·8	24·6	22
Tractive effort, full field (lb.)	285	570	850	1130	1560
Tractive effort, normal field, (lb.)	200	460	725	1000	1410
Tractive effort, weak field (lb.)	127	375	625	900	1300
Efficiency, full field (per cent)	78·3	83	83	82·2	80·5
Efficiency, normal field (per cent)	75	84·2	86·2	85·8	84·5
Efficiency, weak field (per cent)	67	83	86·2	87	86·2

The mean accelerating current with full field is 130 amperes per motor.

The train resistance, calculated from equation (38), is given by $r = 4{\cdot}1 + 0{\cdot}055V + 0{\cdot}0042V^2$, and the apparent train resistance during coasting is obtained by making allowance for the motor and gear friction losses during this period. The values of train and coasting resistances at various speeds are—

Speed of train (ml.p.h.)	10	20	30	40	50
Train resistance (lb. per ton)	5·1	6·9	9·6	13	17·4
Apparent train resistance (lb. per ton)	8·5	10·8	14	17·8	22·4

First, consider this train to operate on a service with 2·06 stops per mile, at a schedule speed of 16 ml.p.h., the duration of each stop being 20 seconds. The distance between the stops is 2560 ft., and the running time is 89 seconds.

For this run the motors will be operated with the full field winding throughout. The initial acceleration (corresponding to a mean current of 130 amperes per motor) is 1·35 ml.p.h.p.s. and occupies 12·6 seconds. Power is cut off at 30·1 seconds from the start, when the speed is 26 ml.p.h. The train coasts for 48·4 seconds, and the brakes are applied when the speed is 21 ml.p.h. The specific energy consumption is 68·7 watt-hours per ton mile, and the total energy consumption is 5·4 kW. hours per train mile. The r.m.s. current per motor for the run is 51·7 amperes.

Second, consider the train to operate on a service in which the average run of 3900 ft. has to be made at a schedule speed of 20·6 ml.p.h., with stops of 20 seconds' duration. The running time is 109 seconds.

For this run the initial acceleration is made with the full field winding, and the acceleration on the speed-curve is made with the normal field winding, the transition from full field to normal field being made at a speed of 17 ml.p.h. Power is cut off at 44·5 seconds (when the speed is

* The effective turns in the field winding corresponding to full, normal, and weak field are in the ratios 1·0 : 0·667 : 0·5. The free-running speeds on level track with the above train are 33·5, 42·5, 47·5 ml.p.h. for the three field strengths.

32·5 ml.p.h.), and the brakes are applied at 95·8 seconds from the start (when the speed is 26·4 ml.p.h.). The specific energy consumption is 68·7 watt-hours per ton mile, the total energy consumption is 5·41 kW. hours per train mile, and the r.m.s. current is 55·6 amperes.

Third, consider the train to operate on a service in which the average run of 5100 ft. has to be made at a schedule speed of 24·1 ml.p.h., the duration of the stops being 20 seconds. The running time is 124 seconds.

In this case the speed-curve running period is made with the minimum number of field turns in circuit. The initial acceleration is made with the full field winding, the transition to the normal field winding is made at a speed of 17 ml.p.h., and the transition from normal to weak field is made at a speed of 19·5 ml.p.h.

Power is cut off at 60·7 seconds from the start (when the speed is 37·5 ml.p.h.), and the brakes are applied at 108·5 seconds from the start (when the speed is 31 ml.p.h.). The specific energy consumption is 72·6 watt-hours per ton mile, the total energy consumption is 5·72 kW. hours per train mile, and the r.m.s. current is 60 amperes.

Fig. 368 shows the speed-time curves for the above runs, together with the current and equipment-efficiency curves.

The equipment is also capable of operating this train to other fast suburban services, as shown below.

Distance between Stops.		Duration of Stop.	Schedule Speed	Running Time.	Time of Cut off.	Duration of Coasting Period.	Specific Energy Consumption.	R.M.S. Current per . .
ft	miles.	sec.	ml p h.	sec.	sec.	sec.	wh/t.ml.	amp.
5370	1·02	20	25·5	124	79	27	80	62·2
6150	1·17	,,	26·4	139	79	43·3	70	59·6
8720	1·65	,,	30·3	176	127	29·4	69	58·6
10560	2·0	,,	32·5	202	162	19	68	57·4

In all the above cases the equipment is not taxed to the limit of its capacity, and ample margin is allowed for making up time lost by slow-downs or signal checks. The hardest of the above schedules is the run of 5370 ft. at a schedule speed of 25·5 ml.p.h. With easier schedules, the specific energy consumption would be lower, but the above may be considered as representative schedules for electric suburban services.

Part III.—Energy Consumption (Alternating-Current Equipments)

The calculation of energy consumption with **single-phase equipments** is slightly more complicated than the above process, as the power factor has to be taken into account. Moreover, the current during the period of initial acceleration is not controlled by rheostats, but by the application of definite voltages to the motor. Hence every notch, if desired, can be used as a running notch.

The method of procedure is, in general, similar to that employed with direct-current equipments, but, owing to the different method of

speed control, the current during the initial period of acceleration is variable, and therefore the increment process must be applied to this period as well as to the succeeding periods. Curves of the accelerating tractive effort and speed (similar to Fig. 359) will, of course, be required for each operating voltage, and a knowledge of the currents at which the transitions are effected will also be necessary.

The calculations involve only the application of the principles already discussed in detail, and should, therefore, present no difficulty.

The curves of Figs. 369, 370, 371 have been calculated for a four-coach, 175-ton, suburban train (equipped with single-phase motors) when

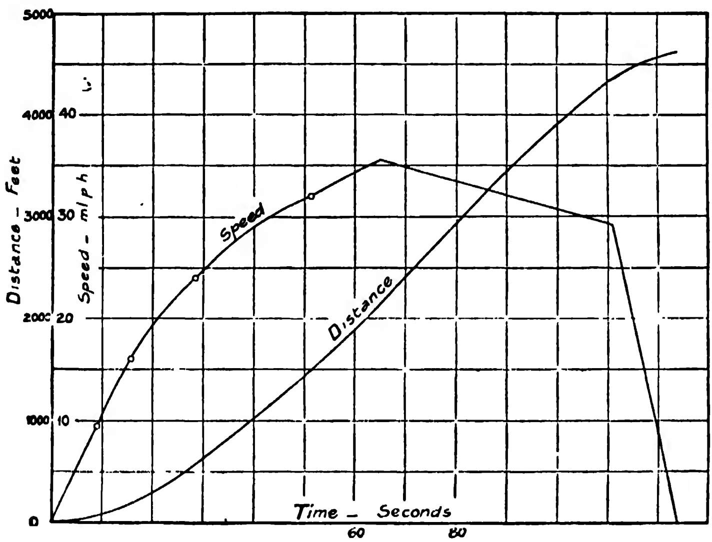


FIG. 369.- Speed-time Curve for Motor-coach Train with Single-phase Motors. NOTE.—The points marked o indicate a change of controller notch.

running, on level track, between stations 4600 ft. apart at an average speed of 25·3 ml.p.h. The current and power curves (Fig. 370) refer to the input to the high-tension side of the transformer (i.e. the input from the 6600-volt trolley wire), the current curve, however, showing the equivalent current per motor and not the total current. The power factor and efficiency curves (Fig. 371) also refer to the high-tension side of the transformer.

The energy consumption is 11·85 kW. hours per train mile, and the specific energy consumption is 67·4 watt-hours per ton mile.

The efficiency curve shows clearly that, although no rheostats are used during the starting period, the average efficiency is fairly low. Moreover, the average efficiency during the period of speed-curve running is below 80 per cent. The low efficiency in the starting period is due to the low power-factor and the relatively large losses in the motors, and this point is frequently ignored in comparisons between single-phase and direct-current equipments. Thus, comparing the efficiency curve given in Fig. 371 with that given in Fig. 367 for a gear ratio of 3·5, we

find that, for the former case, the mean efficiency for the first 12·5 seconds is 47·3 per cent, while in the latter case, the mean efficiency for the first 14 seconds (i.e. the period of rheostatic acceleration) is 52·6 per cent.

The **sustained acceleration** (which is clearly shown in the speed-time curve of Fig. 369) is a special feature of single-phase equipments, and is a result of the inherent characteristics of the motors and the method of voltage control. The feature is also possessed, though not to the same degree, by direct-current equipments with field control (as will be apparent from an examination of the speed-time curves of Fig. 368).

With **three-phase equipments** having rheostatic control, the torque during the initial accelerating period may be maintained approximately

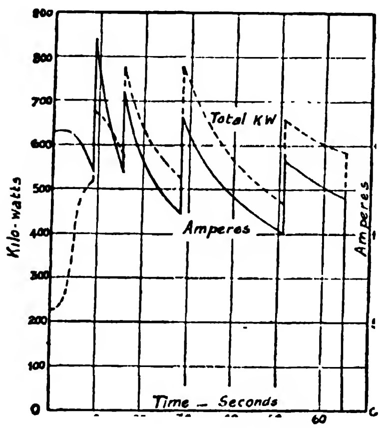


FIG. 370.

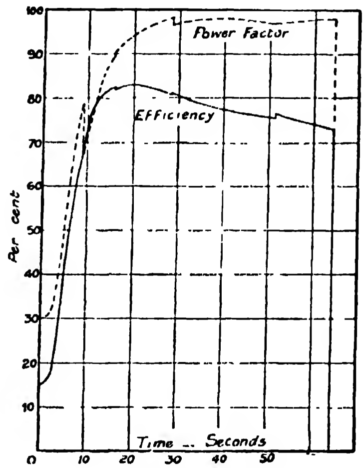


FIG. 371.

FIGS 370, 371.—Current, Power, Efficiency, and Power-factor Curves for Motor-coach Train with Single-phase Motors.

constant, and therefore this period can be calculated in a single step, similar to the direct-current case. The period of speed-curve running, however, is of extremely short duration, owing to the "flat" speed-torque characteristic of three-phase motors. This period is, therefore, calculated in a single step.

With multi-speed pole-changing equipments, starting is effected by varying the voltage applied to the motor and changing the number of poles. Hence, in this case the accelerating periods must be calculated by the increment process, and torque-voltage curves (similar to Fig. 91) will be required for each winding.

With multi-speed cascade equipments, starting is effected by rheostatic control—generally with automatically controlled rheostats—so that the calculations become very simple.

CHAPTER XX

TRAMWAY TRACK CONSTRUCTION

In this country street tramway track is laid with grooved girder rails on a solid foundation of 6 : 1 concrete, at least 6 in. thick. Standard railway practice, on the contrary, aims at a resilient track, the resiliency being obtained by supporting the rails, at frequent intervals, on chairs, and fixing the latter to wooden sleepers on a ballasted foundation. This difference in the track construction of tramways and railways is necessary in order that the tramway track may be suitable for ordinary vehicular traffic, and the grooved girder rail allows the paving to be brought up close to, and level with the top of, the rail.*

The **grooved girder rail** is standardized in four sections, varying from 96 to 113 lb. per yard for straight track. Table XVII gives the principal dimensions of these sections, and Fig. 372 shows details of one section. The **standard width of groove** for straight track is $1\frac{1}{8}$ in., but for curves below 150 ft. radius the groove is widened to $1\frac{1}{4}$ in.

The lip, or check, is $1\frac{1}{4}$ in. below the tread on straight track, but is level with the tread on curved track. The position of the web of the rail and the width of the base are such that the resultant of the forces, due to the weight of the car and lateral pressure of the wheel flanges, falls well within the base.

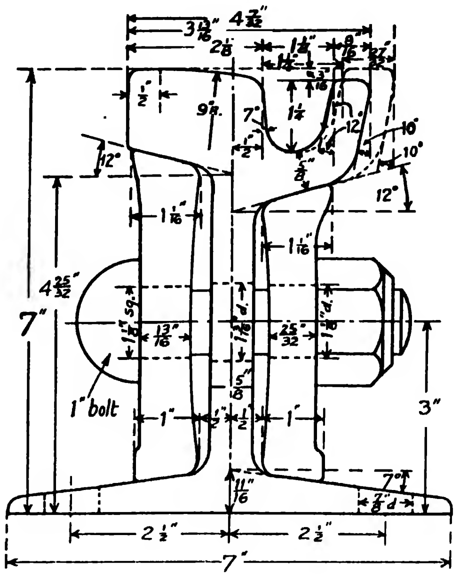


Fig. 372.—Dimensions of B.E.S.A. No. 8 Tramway Rail and Fish-plates. Note - Fish-plates are 2 ft. long and are fastened with six bolts.

Rails of standard section may be obtained in lengths of 35, 45, or 60 ft. for straight track, and 35 ft. for curved track. The 45 or 60 ft. lengths are usually adopted on account of the reduced number of joints in the track.

Composition of rails. Steel for tram rails may be made by either the Bessemer or the open-hearth process. When made by the **Bessemer process,** the limits of the impurities are—

Carbon	0·5 to 0·6 per cent
Manganese	1·0 ,,

* In tramways (or light railways) operating over a private right-of-way, the track is generally laid with sleepers and ballasted in the same manner as railway track.

Silicon	0·1	per cent
Phosphorus	0·05	,,
Sulphur	0·07	,,

For the **open-hearth process** an average composition is—

Carbon	0·65	per cent
Manganese	0·8	,,
Phosphorus	0·03	,,
Silicon	0·14	,,
Sulphur	0·03	,,
Iron	98·35	,,

The **influence of the various constituents** on the physical properties of rail steel can be stated thus—

Carbon, manganese, phosphorus, and silicon have a tendency to harden. Manganese, in sufficient quantity, secures more uniform distribution of the carbon, and, in large quantities, gives extreme toughness and ability to resist abrasive wear. Steel containing a large proportion of manganese is practically non-magnetic, and has a much higher electrical resistance than ordinary steel. Silicon, in larger quantities than those given above, will cause the steel to be irregular and brittle after rolling. Phosphorus produces greater hardness than carbon or silicon, but results in "cold-shortness." Sulphur has little effect on the tensile strength or ductility, but in excess of 0·08 per cent gives seams and cracks in rolling, and also "hot-shortness."

TABLE XVII

Dimensions of British Standard Tramway Rails and Fish-plates

	Tramway Rails.						Fish-plates.	
B.S. Section.	Weight of Rail (lb. per yard).	Height of Rail.	Width of Flange.	Thickness of Web.	Overall Width of Head and Lip.	Width of Head at Tread.	Weight of Inner Plate.	Weight of Outer Plate.
		in.	in.	in.	in.	in.	lb.	lb.
6	96·4	$6\frac{1}{2}$	$6\frac{3}{4}$		$3\frac{3}{4}$	$2\frac{1}{8}$	$22\frac{1}{2}$	27
6c	103·2	,,	,,	$\frac{13}{32}$, $\frac{15}{32}$	$4\frac{7}{32}$	,,	,,	,,
7	103·7	7	,,	--	$3\frac{13}{16}$	,,	26	$30\frac{1}{2}$
7c	109·7	,,	,,	$\frac{7}{16}$, $\frac{1}{2}$	$4\frac{7}{32}$	,,	,,	,,
8	112·9	,,	7	$\frac{5}{8}$	$3\frac{15}{16}$	,,	25	,,
8c	119·2	,,	,,	,,	$4\frac{7}{32}$	,,	,,	,,
10	95·4	5	6	$\frac{9}{16}$	$3\frac{13}{16}$	,,	$10\frac{1}{2}$	$13\frac{1}{2}$
10c	101·8	,,	,,	,,	$4\frac{7}{32}$	,,	,,	,,

Notes. *c* denotes section for curved track. Sections Nos. 6 8c are in general use for street tramway track. The dwarf Sections, 10, 10c, are intended for carrying heavy loads on sleeper track. The depth of groove is $1\frac{1}{16}$ in. for Nos. 6, 7; $1\frac{1}{4}$ in. for Nos. 6c, 7c, 8, 10; and $1\frac{7}{16}$ in. for Nos. 8c, 10c. The lip is $\frac{1}{2}$ in. for No. 6; $\frac{9}{16}$ in. for Nos. 7, 8, 10; $\frac{27}{32}$ in. for Nos. 6c, 7c, 8c, 10c. Fish-plates are 2 ft. long for Sections Nos. 6–8c, and 1 ft. 6 in. long for Nos. 10, 10c.

Where rails are liable to excessive wear, it is desirable to use a high-silicon steel, made by the **Sandberg process,** having a composition as follows—

Carbon	0·4	per cent
Manganese	1·25	,,
Silicon	0·3	,,
Phosphorus	0·07	,,
Sulphur	0·07	,,
Iron	97·91	,,

In the Sandberg process the silicon is introduced—in the form of high-percentage silico-spiegel—*after* the crude steel has been purified. By this method the brittleness due to high silicon is avoided, and the steel is dense, tough, hard, and fine grained. The rail wear with this steel has been found to be from 35 per cent to 40 per cent less than that with steel made by the Bessemer process.

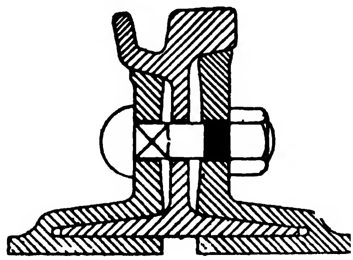


FIG. 373.—"Continuous" Rail-joint.

Rail joints. Individual rails may be connected together mechanically by fish-plates, or may be welded to form one continuous length. The **fish-plate joint** (Fig. 372) consists of two curved plates—placed one on each side of the web of the rail—with inclined or "fishing" surfaces fitting between the head and flange of the rail, and bolted together with six bolts. It is essential that the fishing surfaces should be a good fit, since the life and strength of the joint is dependent on this condition. As the life of a rail is largely influenced by wear at the joint, and the latter is inaccessible for inspection and adjustment, the importance of good joints on a tramway track is very great.

A modification of the fish-plate joint is shown in Fig. 373, and is known as the **continuous rail-joint.** This joint provides larger bearing surfaces than the ordinary fish-plates, as well as greater vertical stiffness.

Where ordinary fish-plates are used, increased vertical stiffness can be obtained by bolting (across the joint) a short length of rail (inverted) to the underside of flange of track rail (see Fig. 391, p. 548). This method has been largely adopted, and it is also useful for anchoring purposes.

Welded joints are extensively used at the present day, as this method of jointing the rails provides a solution to track troubles due to faulty mechanical joints. The processes in use are the "Thermit," the oxy-acetylene, and the electric arc.

The **Thermit process** of rail welding depends upon the fact that aluminium, in a finely divided state and under certain conditions of temperature, is a powerful reducing agent. Thus, if a mixture of iron oxide (Fe_2O_3), flux, and finely divided aluminium is heated to about 2000° F., an exothermic reaction takes place, producing a temperature of from 5000° to 6000° F., and giving molten iron and aluminium oxide ($Fe_2O_3 + 2Al = 2Fe + Al_2O_3$). In the **practical application** of the Thermit process, a powder, consisting principally of a mixture of finely divided

aluminium and iron oxide, is ignited (by a suitable ignition powder) in a special crucible arranged for tapping from the bottom, and the molten steel is run into a mould placed round the web and flange of rail. The rail ends and molten steel are thereby fused together, and a butt weld at the

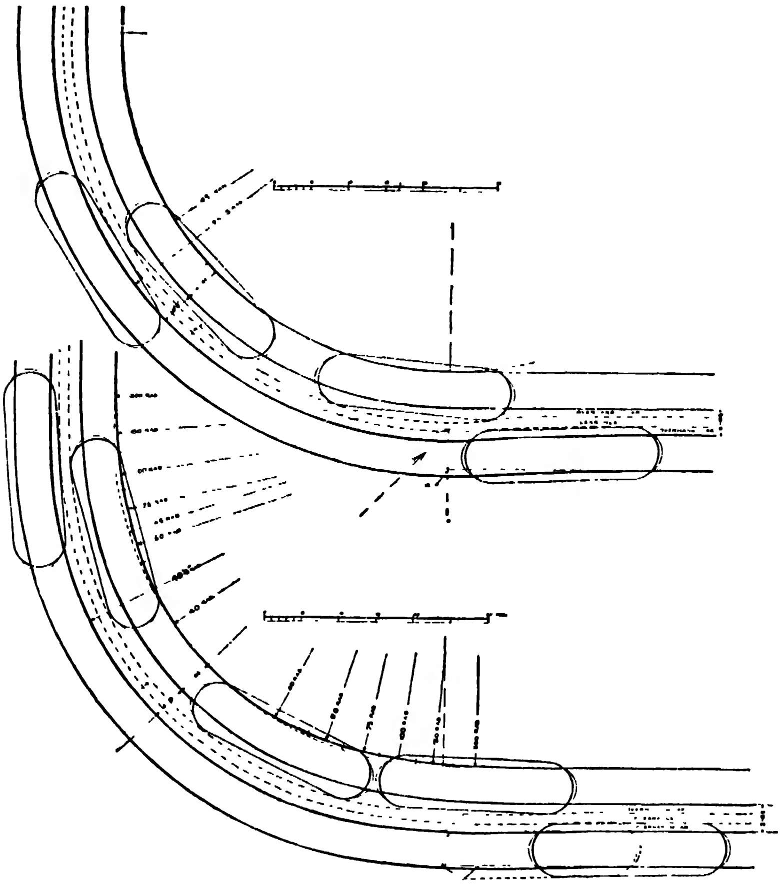


FIG. 374.—Layout of Double Track with Simple (upper diagram) and Compound (lower diagram) Curves (single-truck car, 6′ 6″ wheel base, 15″ minimum clearance between cars).

rail head is obtained by drawing together the special clamps (fitted to the rail ends) a few minutes after tapping the crucible. The mould is designed to give a band of metal, about 3 in. wide, round the joint, so that the strength is practically equal to that of the rail.

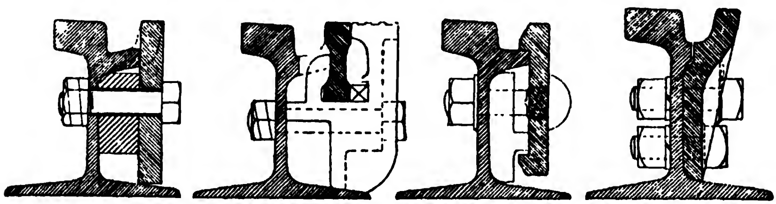
In the oxy-acetylene and electric arc methods of rail welding, fish-plates are spot-welded to the rail ends at each joint. The current for the electric method is obtained from a portable generator having suitable characteristics.

Special trackwork. Trackwork at curves calls for special consideration where the radius is below 150 ft. In these cases the curve should be

compounded with a spiral, in order to give an easier entrance, and to reduce the wear on wheel flanges and rails. With a spiral entrance the spreading of the track at the centre of the curve, to give the necessary statutory clearance of 15 in. between passing cars, is less than that required for a curve of uniform radius. This is shown in Fig. 374.

Where curves below 50 ft. radius are traversed by single-truck cars, considerable wear occurs on the check of the inner rail, due to the grinding action of the wheel flanges. In order to avoid having to renew a rail solely on account of a worn check, a modification of the standard rail with a renewable check has been developed.*

The four types of renewable checks in use in this country are shown in Fig. 375. The Hadfields' type (*A*) consists of a rolled plate of "Era"† manganese steel. The Holt type (*B*) consists of a special check rail (of rolled manganese steel), which is keyed in chairs bolted to the web of the track rail. A rolled manganese steel check rail is adopted in the London County Council type (*C*), but in this case the check rail is bolted to the track rail, which is a special ("step") rail without a lip. In the



A *B* *C* *D*

FIG. 375.—Types of Renewable Checks for Tramway Rails. *A*, Hadfields; *B*, Holt; *C*, London County Council; *D*, Bulfin.

Bulfin type (*D*) the check is made in sections (of cast manganese steel), which are bolted directly to the web of the track rail.

Points and crossings are required in connection with special track-work, such as loops or turnouts (passing places for cars on single lines), cross-overs, junctions, etc.

All points are made of manganese steel, with the tongues and grooves shaped to standard radii (100, 150, 200, 300, and 350 ft.). The overall length may be from 10 ft. to 15 ft. 6 in., with tongues from 7 ft. 6 in. to 10 ft. long. Illustrations of typical modern points are given in Figs. 376, 377, 379.‡

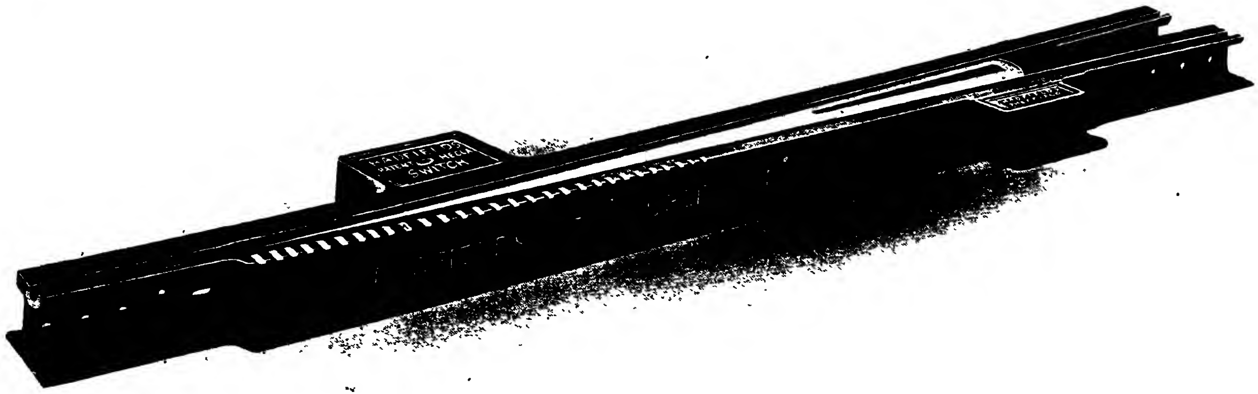
Points can be divided into three classes, viz. (1) open or fixed points, sometimes called "mates"; (2) movable points; (3) automatic or spring points.

Open points have no tongues, and are used in conjunction with

* Messrs. Hadfields manufacture rails for curves in *solid manganese steel*, which material is able to resist successfully the grinding action of the wheel flanges. It should be remarked that, on curves, the groove is worn at the check on the inner rail, and at the tread on the outer rail.

† "Era" (patent) manganese steel is a speciality of Messrs. Hadfields. The steel receives special heat treatment during manufacture: its chief properties are hardness, toughness, and ability to resist abrasive wear.

‡ The author is indebted to Messrs. Hadfields for the illustrations of points and crossings in this chapter and in Chapter XXI.



FIGS 376, 377.—Hadfields' Tramway Points. FIG. 376, Open point; FIG. 377, "Hecla" movable point.

movable points, but in some cases a pair of open points (or " mates ") are used under trailing conditions.

A **movable point** has a tongue which is operated either by a crowbar or through levers from the side of track. This class of point is used at turnouts, cross-overs, and junctions.

An **automatic point** has a tongue which is spring controlled, and is operated by the flanges of the car wheels. The tongue is kept in position for one direction of traffic by a spring, and is therefore self-setting when operated as a trailing point by a car coming from the other direction.

Very frequently a pair of movable or automatic points is used, as the use of double-tongue points conduces to smoother running than is possible where open mates are introduced. The tongues are connected together by a suitable rod enclosed in a box, Fig. 378. Sometimes, where the points are only trailed through, or where they are only faced for deviation in one direction (in which case the mechanism controlling the tongues

FIG. 378. Hadfields' " Hadura " Tramway Switches.

is set for automatic return), the connecting rod is omitted. Each point of the pair is then independently controlled.

Two examples of universal spring points (which may be used as either automatic or movable points) are shown in Fig. 377 and Fig. 379. The operating mechanism of the point of Fig. 377 is shown in Fig. 380. This mechanism consists of a spring plunger combined with a rocking lever to which the tongue of the point is mechanically connected. The fulcrum of the rocking lever *A* is adjustable, and may occupy any of the three positions shown, according to the class of point desired.

This point (Fig. 377) has other special features. Thus the body and the tongue are made of " Era " manganese steel, and the tongue is of the " pinless " variety. The heel (or hinge) fits into a dovetail recess in the body of the point and is maintained in its correct position by an adjustable block. A detail of the heel is shown in Fig. 381 ; the adjustable block being shown, detached, at *A*, and the adjustment packing pieces at *B*. The dovetail recess in the body, and also the heel of the tongue, are both ground to give a perfectly fitting joint, while the whole of the underside of the tongue, and the bed (in the body) on which the tongue moves, are also ground to true surfaces.

The latest improvement in heel-end design is shown in Figs. 379 and 381(*b*). In this design the heel (or hinge) has a specially large bearing

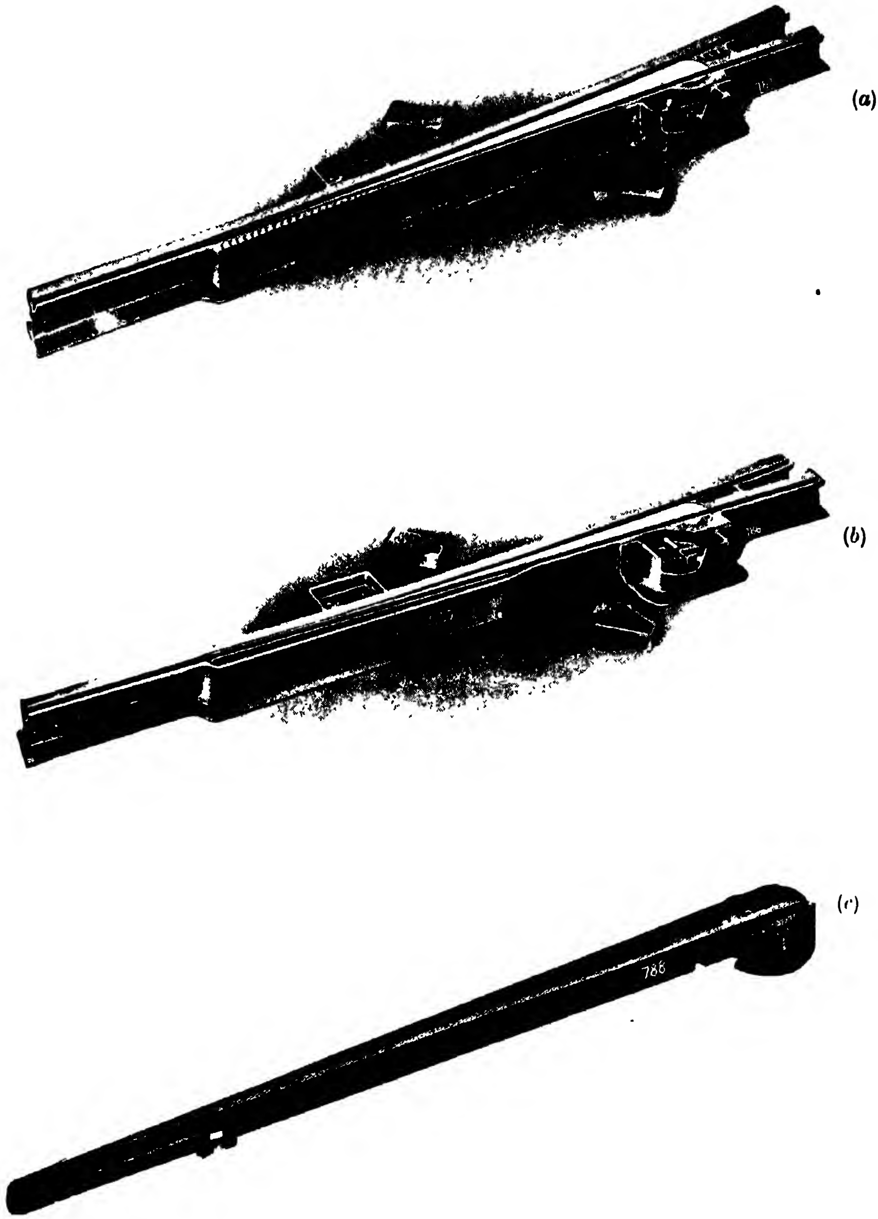
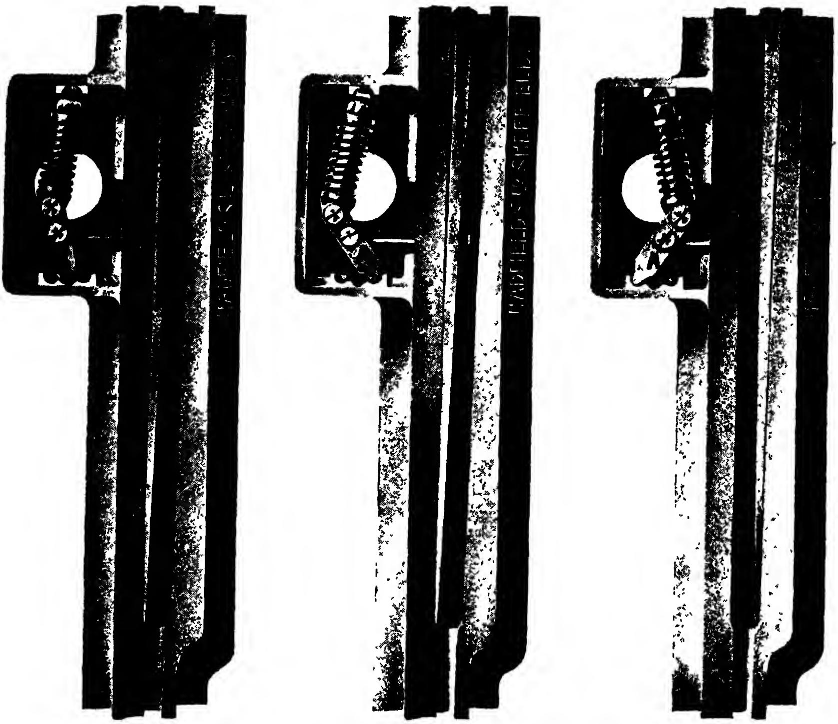


FIG. 379.—Hadfields' "Hadura" Tramway Points with Pinless Tongues. (a) Point with Ordinary Tongue; (b) Point with Grooved Tongue; (c) Tongue.

area, viz. about 60 sq. in.; and as the tread is carried through the centre, the rolling load is better distributed, and the wear is more uniform. The heel of the tongue is securely held down on its bearing surface by means of the sliding block, and the adjustment to take up any wear is automatically secured by means of a spring-operated adjusting wedge. The box containing the fittings at the heel end of this type of point is also used for drainage purposes, so that the point is drained at both ends,



(a) Movable Point. (b) Automatic Pulling Point. (c) Automatic Pushing Point.

FIG. 380.—Universal Operating Mechanism of Hadfields' "Hecla" Point.

which, of course, facilitates the keeping of the tongue recesses free from silt, etc.

Crossings are usually single castings of manganese steel. For turnouts and cross-overs they are standardized with angles from 1 in 4½ to 1 in 8, and lengths varying from 7 ft. to 11 ft.

The **applications of points and crossings to special track-work** are shown in the diagrams of Fig. 382.

A **turnout** requires a crossing, an open point, and an automatic point at each end.

A **single junction** or **cross-over** requires at each end a crossing and a pair of points, which may consist either of a pair of movable points or a movable point and an open mate.

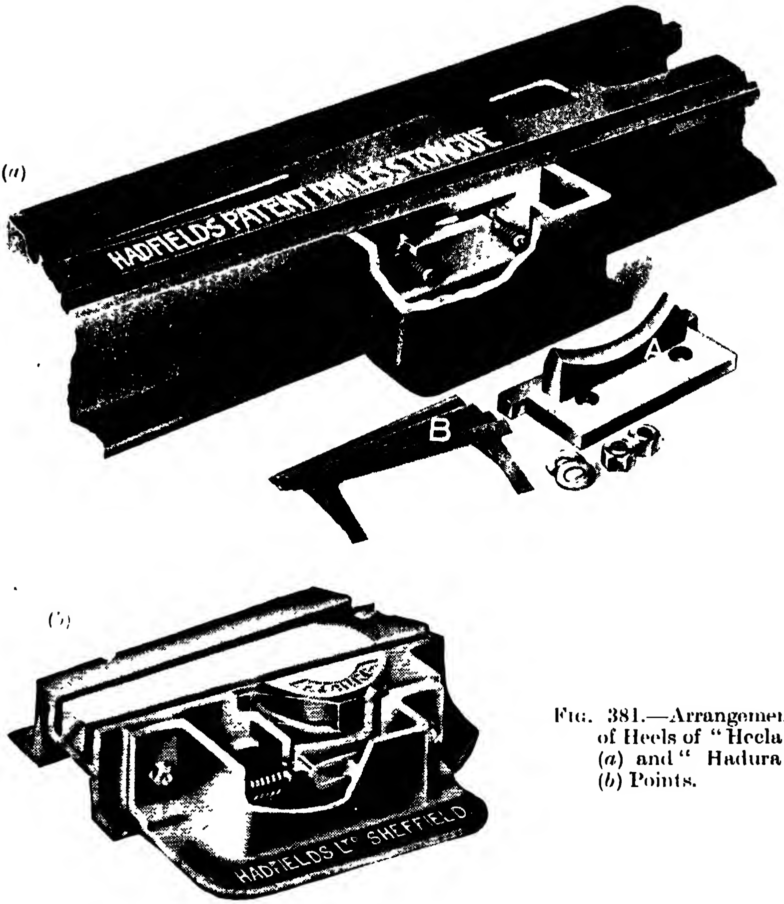


FIG. 381.—Arrangement of Heels of "Hecla" (a) and "Hadura" (b) Points.

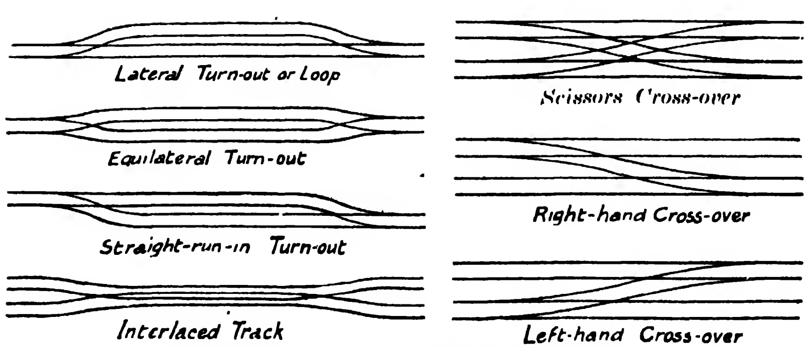


FIG. 382.—Examples of "Special" Trackwork.

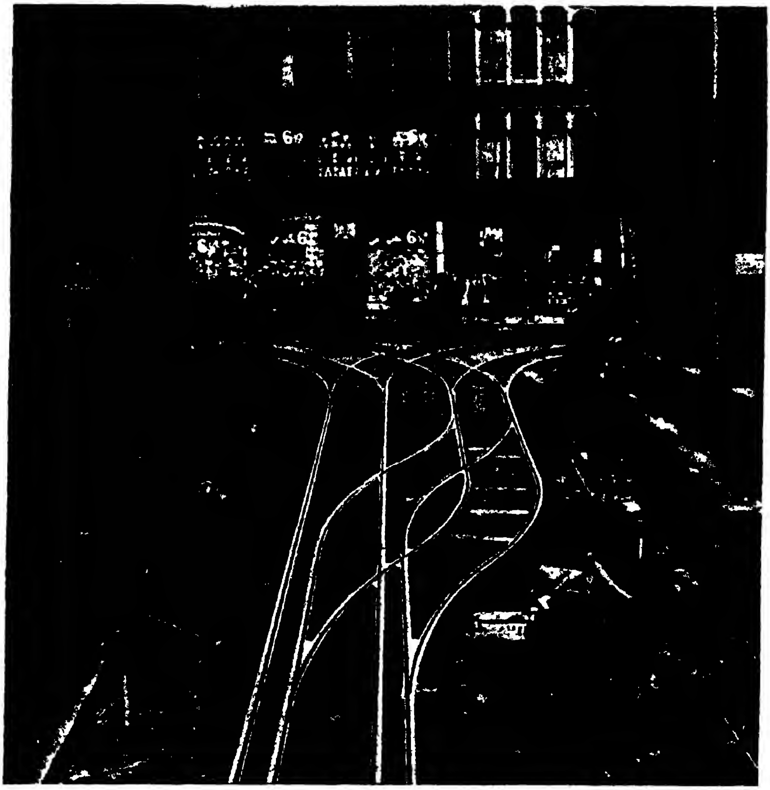


FIG. 383.—Interlacing of Tracks at Double-track Junction (Track-work by Hadfields)

FIG. 384.—Oerlikon Point Magnet. (The tongue of the point is operated by a bell-crank lever fitted to the projecting spindle.)

A **double junction** or **scissors cross-over** requires four pairs of points and eight crossings, the points being of either the movable or automatic types for facing or trailing positions. Alternatively, movable points and open mates—arranged in pairs—may be used.

Interlaced track requires only a crossing at each end. This form of special track-work is used at places (on a line of double track) where there is insufficient room for double track, and it possesses advantages over the use of single track at those places. Thus, points are not required, while the wear on the rails is uniform throughout the sections of double track and interlaced track. A practical example of interlaced track is illustrated in Fig. 383.

Electrically-operated points. At junctions in busy thoroughfares it is desirable to operate the points without manual labour, which can be arranged without difficulty on overhead systems. For example, the tongue of the point may be operated by an electro-magnet (one form of which is shown in Fig. 384) which is excited by the line current from a special overhead fitting in advance of the junction. If the point is required to be operated, the motorman keeps the controller in the first power position when passing this contact, while, if the car is to run through, the controller is kept "off."*

* See *Journal of the Institution of Electrical Engineers*, vols. 35 (p. 587), 44 (p. 470), for details of the Tierney-Malone electrically-operated point-shifter.

CHAPTER XXI

TRACK CONSTRUCTION FOR CONDUIT TRAMWAYS

THE only example in this country of a conduit tramway is in London (London County Council tramways), and comprises 122 miles of route (96 per cent being double track) over the greater portion of which the traffic is exceptionally heavy.

The **principal features** of the L.C.C. conduit system—which is of the centre-slot type—are—

(1) The track rails, together with the slot rails, are supported by "extended" yokes (weighing 400 lb.) at intervals of 7 ft. 6 in.

(2) The slot rails are further supported by "short" yokes (weighing 200 lb.), spaced midway between the extended yokes.

(3) The slot is 1 in. wide.

(4) The conduit has a width of 16 in. and a total depth of 24 in.

(5) The joints in the track rails are welded.

(6) The insulator "pockets" are enclosed with non-removable covers cemented in position.

Views of track construction in progress are shown in Figs. 385, 386.

The **procedure in laying the track** is briefly as follows: The roadway is excavated and the yokes are placed in position. The track and slot rails are then placed in position and lined up, the slot rails being bolted directly to the yokes, but a hardwood packing strip ($\frac{5}{8}$ in. thick) is inserted between the flanges of the track rails and the (extended) yokes which support them. The gauge is adjusted with the aid of taper keys (which can be seen in the foreground of Fig. 385), and the alignment of slot rails is effected by the tie bars at each yoke (Fig. 386).

After the track rails have been lined up and levelled, the yokes are set in 6 to 1 concrete. The centering (*A*, Fig. 386)—by means of which the correct shape is given to the conduit—is next placed in position between the yokes, after which the paving strips *B* and boxes *C* (for the insulator pockets) are fixed, as shown in Fig. 386. The temporary packing blocks under the track rails (see Fig. 386, left-hand track) are then removed, and the space up to the flanges of the rails is filled with 6 to 1 concrete.

Other features of the track construction are—

The **centring** (which is placed temporarily between the yokes to form the shape of the conduit) was originally constructed of wood, but on straight track a collapsible sheet-iron centring is now used. This is constructed in lengths 3 ft. 9 in. long, and consists of two sheets, hinged together at the bottom, and pressed against the yokes by toggle joints at each end. When the concrete has set, the centring can be made to collapse, and can be extracted through openings which have been left for that purpose. At special track-work the wooden type of centring is used, and a portion of this is shown lying by the track in Fig. 386.

The **paving strips** *B* (Fig. 386), which consist of lengths of $2\frac{3}{4}$ in. by $\frac{3}{8}$ in. wrought iron fitting in grooves in the yokes, are for the purpose

FIG. 385.—Track Construction in Progress, showing Yokes, Rails, and Tie-bars in Position.

FIG. 386.—Track Construction in Progress, showing Centring in Position.

of preventing the concrete next to the flange of the slot rail from breaking away.

The **insulator pockets** are placed 15 ft. apart, and the insulators are bolted to the flanges of the slot rails, as shown in Fig. 388. Details of the insulators are given in Fig. 387.

Each insulator pocket is covered by a cast-iron plate (Fig. 389), which is supported partly on the flange of the slot rail and partly on the

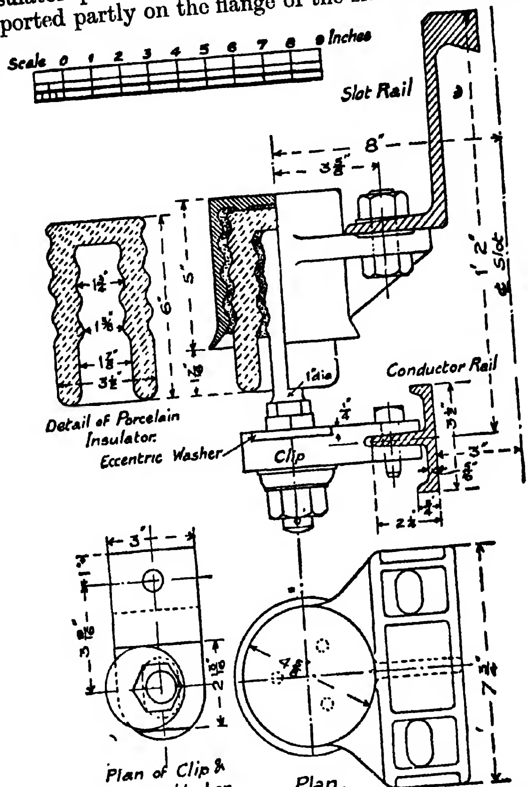


FIG. 387.—Details of Insulator for Conduit Tramways.

concrete, and is finally cemented in position. In order to indicate the position of these covers on the road surface, a special square sett or block is placed over each when the paving is laid. With this construction a faulty insulator is accessible only after the paving and the cover plate have been removed. This feature is not considered to be a disadvantage in practice: for, in the first place, the insulators are very reliable; and, secondly, the sealing up of the insulator pocket prevents the ingress of mud, etc.

The **conductor rails** are of "T" section and weigh 22 lb. per yard. They consist of high conductivity steel, having a specific resistance of 4·25 microhms per inch cube. The joints are bonded with two flexible bonds having $\frac{7}{8}$ in. terminals expanded into the rails.

Section insulators, consisting of a 2 ft. gap in the conductor rails, are placed at intervals of half a mile, at which points cables are connected to the feeder pillars and sub-station. (See Chapter XXVI for details of these pillars.) Each end of the conductor rail is flared back 1½ in. in

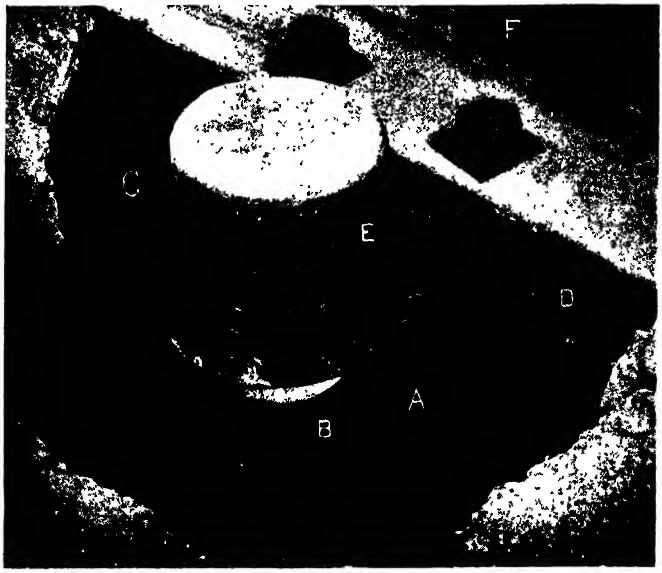


FIG. 388.—Insulator and Conductor Rail in Position in Conduit. *A*, Double Clip; *B*, Eccentric Washer; *C*, Conductor Rail; *D*, Bonds; *E*, Insulator; *F*, Slot Rail.

order to prevent the shoes of the plough from fouling, and at these points each rail is supported by two insulators arranged as in Fig. 390.

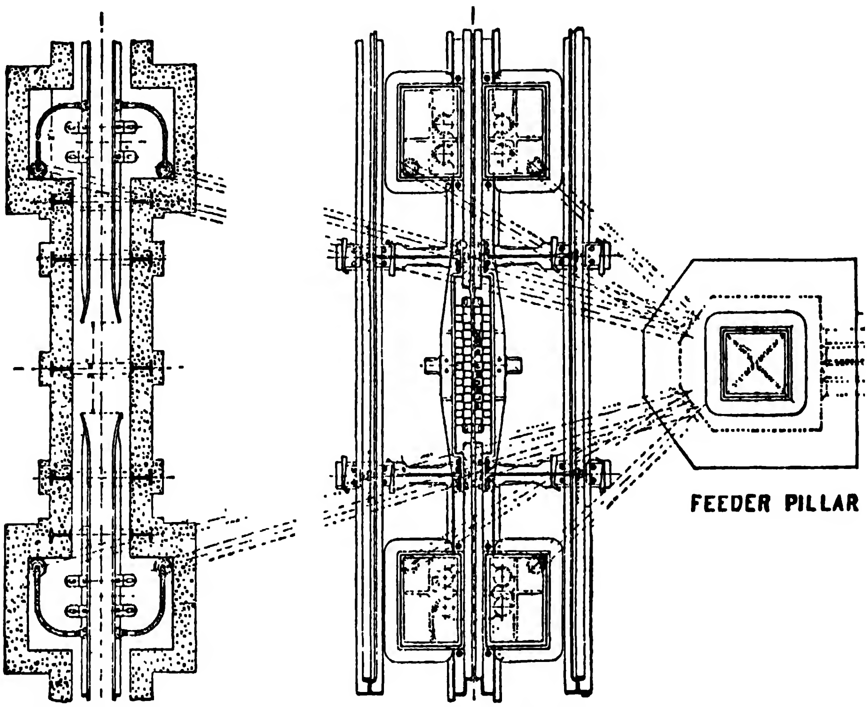
A "plough hatch" or "plough box" is usually fitted in the slot rails

FIG. 389.—Insulator Cover Plates.

at each section insulator. This consists of two removable plates, each about 3 ft. long by 4 in. wide, which, when removed, leave a fairly large opening over the conduit, through which a plough can be withdrawn.

Special work. In conduit tramways the track-work at cross-overs

and junctions is considerably more complicated and costly than that at similar places on tramways operating on the overhead system, since not only must a clear passage be provided under the roadway for the plough, but special points are required for the slot rails as well as for the track rails. The amount of exposed metal at the road surface will, therefore, be considerable, while the amount of metal below the road surface will



Sectional Plan, showing Section Insulator and Cable Connections.

Plan, showing Yokes, Plough Box, and Insulator Cover-plates.

FIG. 390.—Section Insulator and Plough Box (L.C.C. Tramways). NOTE—The cable ducts from conduits to feeder pillar are shown in dotted lines.

be still greater, on account of the extra yokes and gussets which are required for supporting the special work.

The nature of the special work for a double-track crossing is shown in Fig. 391, and the special work for a cross-over is shown in Fig. 392. These illustrations refer to track-work for the L.C.C. tramways, and show this work assembled on the lay-out floor at Messrs. Hadfields' works. Only the special work is shown assembled, the standard yokes and other fittings being omitted.

The points, crossings, and other parts subjected to wear are constructed of manganese steel, while the remaining portion (with the exception of the rails and fastenings) is of cast steel. It will be observed that the points in the slot rails are placed after those in the track rails,

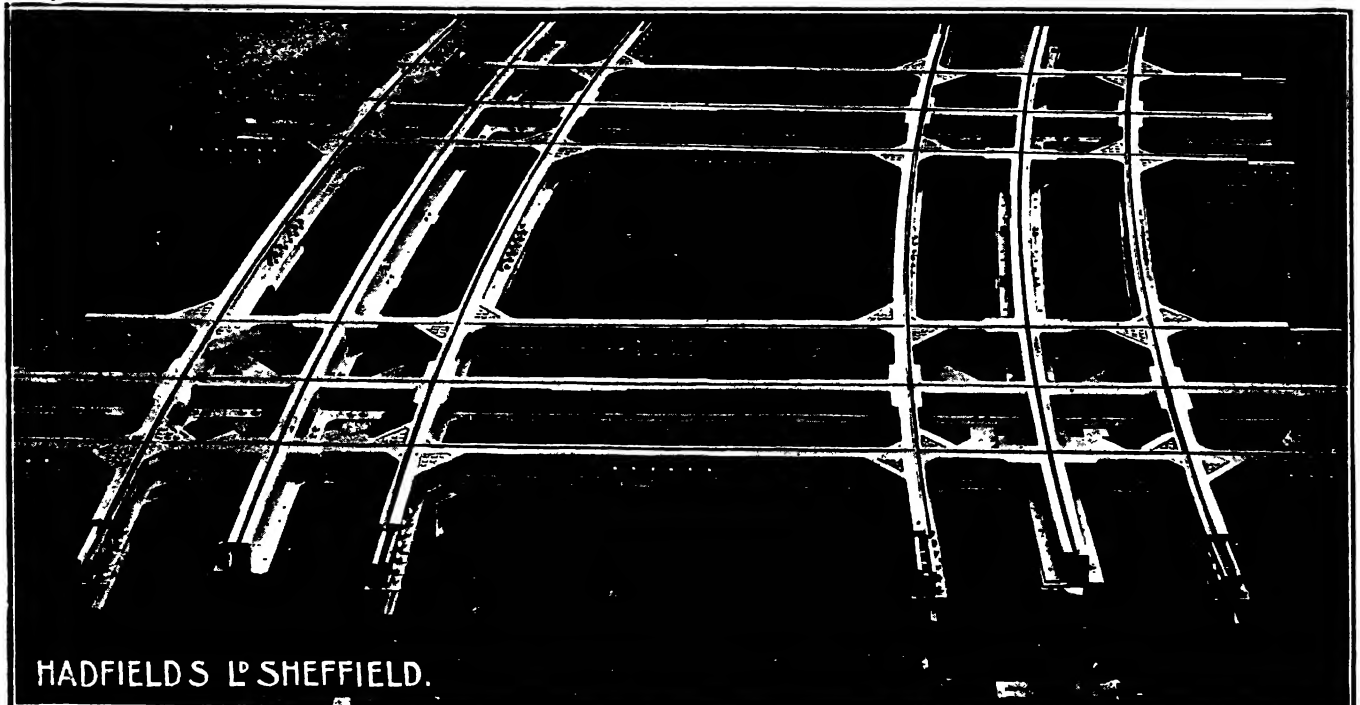


FIG. 391.—Special Track-work for Double-track Crossing (London County Council Conduit Tramways). Attention may be directed to the complicated nature of the manganese steel castings required for special track-work of the type illustrated above and in Fig. 392.

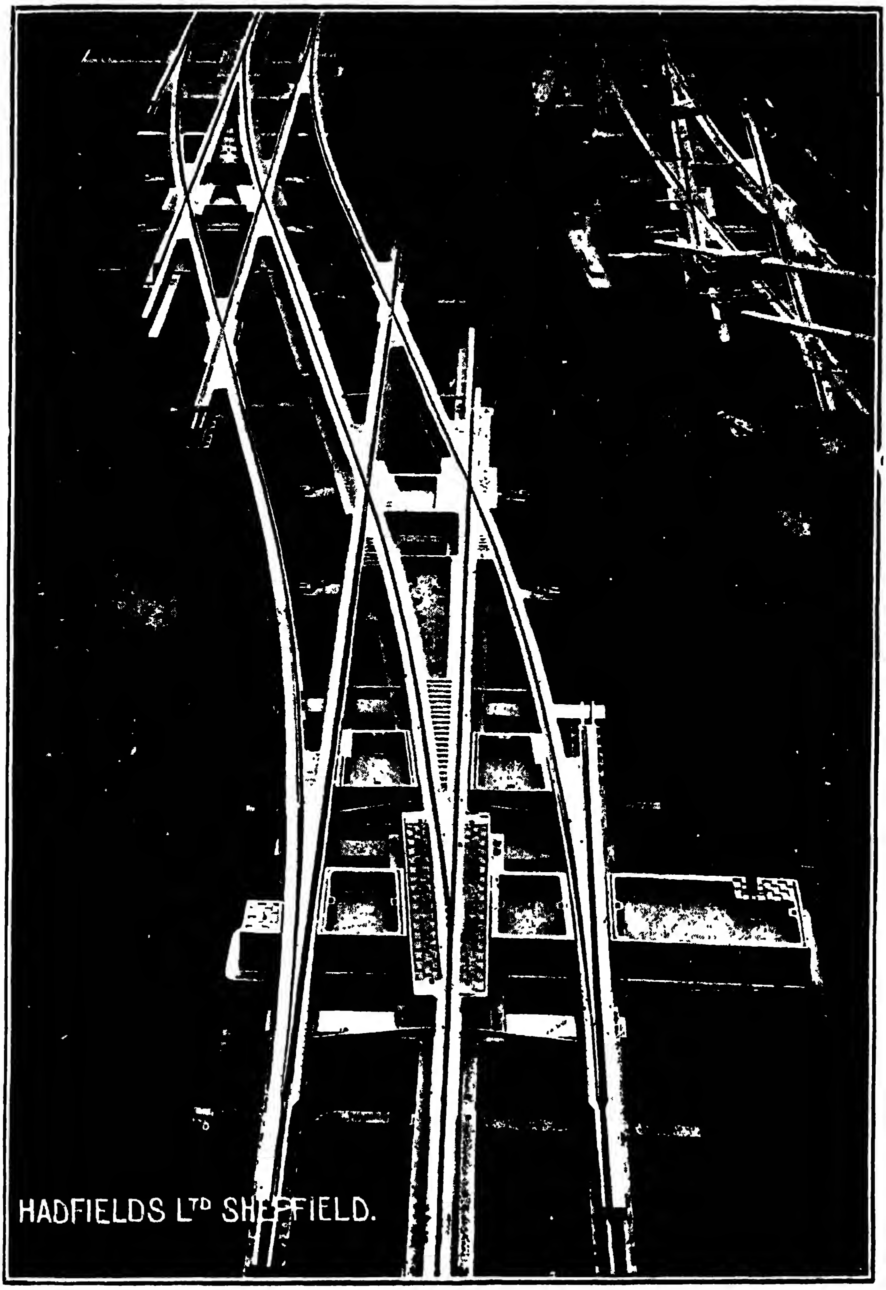


Fig. 392.—Special Track-work for Left-hand Cross-over (London County Council Conduit Tramways).

so that the car will be on the correct road before the plough meets the points.

The **points for the slot rails** are of a special design, and are shown in Fig. 393. Each slot-point consists of two leaf-tongues, which move under protecting covers, the latter being flush with the road surface.

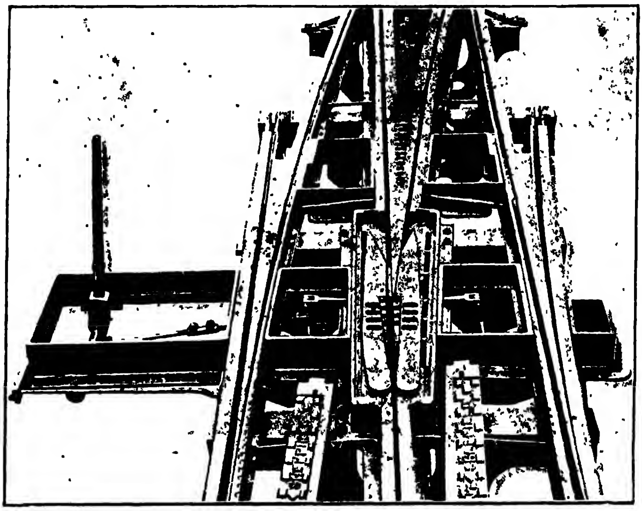


FIG. 393.—Hadfields' Centre-slot Point for Conduit Tramways. View with protecting covers removed, showing leaf tongues and operating mechanism

The tongues are operated, through suitable mechanism, by a lever inserted in a slot at the side of the track. (In Fig. 393 the covers have been removed to expose the tongues and operating mechanism.) In

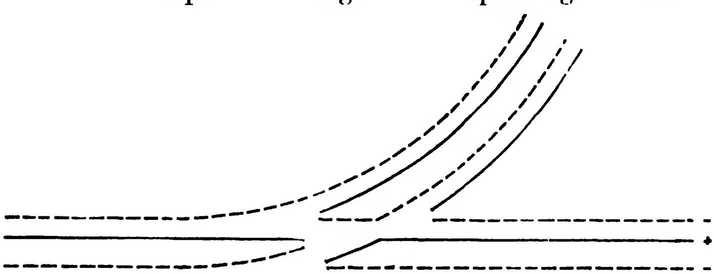


FIG. 394. Arrangement of Conductor Rails at Double Track Junction.

the straight-run-through position one leaf-tongue guides the plough past the throat of the point, while in the branch position this tongue moves under its cover-plate, and the other leaf-tongue moves out to guide the plough to the branch track.

In order to provide a clear passage for the plough in each direction, it is necessary to insert long breaks—amounting to 12 ft. or more—in the conductor rails, the disposition of the latter being indicated in

Fig. 394. At important junctions the various sections of the conductor rails are connected to switches in feeder pillars, and in other cases they are interconnected by jumper cables laid in suitable ducts.

The **twin-slot** is another example of special work which has been adopted in some parts of London where the road is not wide enough for double track. In this case a single pair of track rails is provided with two conduits, thereby avoiding the complication of slot points.

Drainage. It is very important that efficient means be adopted for preventing any accumulation of surface water or mud in the conduit. The following method is adopted in London. The track rails are drained by drain boxes, connected to the conduit through 3 in. pipes. (These drain boxes can be seen in Fig. 386.) The conduits are drained into sump pits, spaced at intervals of 120 ft. along the track, the pits being constructed of concrete and placed in the clearway between the tracks. Each sump pit has a maximum depth of 7 ft. 9 in., the catch-pit being 3 ft. 6 in. deep by 3 ft. by 2 ft. The upper portion of the pit extends the full width between the conduits, which terminate at each wall. In this manner a depositing bench—for mud from the conduits—is formed. The removal of the mud and the flushing of the pit is performed periodically. The catch-pit is connected to the sewer by a 9 in. pipe, the sill of which is 2 ft. 5 in. above the bottom of the pit. The mouth of the pipe is provided with an iron hood arranged to give a water seal 5 in. deep.

It is, of course, necessary to provide means for withdrawing any mud from the bottom of the conduits into the sump pits, as the natural drainage cannot be relied upon to do this effectually unless the road is on a gradient. A scraper is used for this purpose, and is either manually operated or drawn through the conduit on a special framework attached to a car.

Combined conduit and overhead trolley systems. On some parts of the L.C.C. tramway system the cars operate on both the conduit and overhead trolley systems. At the termini of the conduit system the plough is deflected into the clearway between the tracks, the conductor rails terminating a short distance previous to this deflection. The plough is run off the plough carrier on to a small trolley by the combined motion of the car and the deflection of the slot, the weight of the plough during the transition period being taken on a special fork placed in the plough carrier by a tracksman. The plough, on its trolley, is then run into position for being placed on a car on the adjacent track.

CHAPTER XXII

THE TRAMWAY TRACK CONSIDERED AS AN ELECTRICAL CONDUCTOR

In tramways operating on the overhead system the track rails, in conjunction with feeder cables, form the return conductor to the negative terminal of the generators. The electrical properties of the rails and track therefore require consideration.

The **specific resistance** of steel, having the same composition as standard Bessemer tram rails, averages 7·5 microhms per inch cube at a temperature of 20° C. The cross-sectional areas of rail sections Nos. 6, 7, 8 are 9·64 sq. in., 10·37 sq. in., and 11·29 sq. in. respectively, and the resistances per foot are 9·33, 8·67, 7·96 microhms respectively.

Track as electrical distributing system. From these data we observe that the resistance of a mile of *continuous* rail is of the order of 0·05 ohm. But when a track is laid with commercial rail lengths jointed mechanically, the fish-plate joints have a high resistance relative to the rail. Therefore, to obtain good conductivity for the track as a whole, either this type of joint must be eliminated by welding the rails, or it must be supplemented with a good conductor or " bond."

A rail joint having a low resistance is necessary, not only for reasons of economy, but on account of statutory regulations, which limit the voltage drop in the rails to 7 volts and the voltage between any pipe and the rails to 1 volt positive and 3 volts negative.

These regulations were made at a time when considerable trouble was being experienced (due to the corrosion of water and gas pipes and lead cable sheaths) by the stray currents resulting from imperfect bonding of the rail joints. The magnitude of this corrosion has been demonstrated by Mr. I. H. Farnham, in a paper on "The Destructive Effect of Electric Currents on Subterranean Metal Pipes."* In this paper it is shown that the corrosion of the pipes was due to (*a*) the positive terminal of the generator being connected to the rails, and (*b*) imperfect bonding of the rail joints, so that the pipes acted as feeders to the rails. The current left the pipes for the rails at numerous points, and as each point, with the surrounding soil and rails, formed an electrolytic cell in which the pipe was the anode, the corrosion was considerable.

The methods adopted as a remedy for these troubles were: (1) to connect the negative terminal of the generator to the rails ; (2) to bond the rail joints and cross-bond the rails ; (3) to bond pipes to the rails when the former were in close proximity to the latter ; (4) to lay cables from the negative bus-bar to the pipes which were positive to the rails under the new conditions, the object of the cables being to lead the current out of the pipes by a path of low resistance.

The first three methods are incorporated in the Ministry of Transport Regulations, and the fourth method has been superseded by the more

* *Trans. A.I.E.E.*, vol. 11, p. 191.

satisfactory method of limiting the voltage drop in the rails (i.e. the E.M.F.s causing leakage currents).

In order to maintain the voltage drop in the rails within the limit of 7 volts, "negative" feeders will usually be necessary (i.e. cables connecting various points of the rails to the negative bus-bar). With a properly designed feeder system and the voltage drop in the rails within the above limit, there are practically no corrosion troubles, even on extensive tramway systems.*

Bonds. Modern bonds are of the flexible type and are designed to be as short as the conditions of location will permit, in order to reduce to a minimum the resistance of the joint.

The bonds are usually fixed under the fish-plates, as shown in Fig. 395, as they are then protected from damage when repairs to the paving are

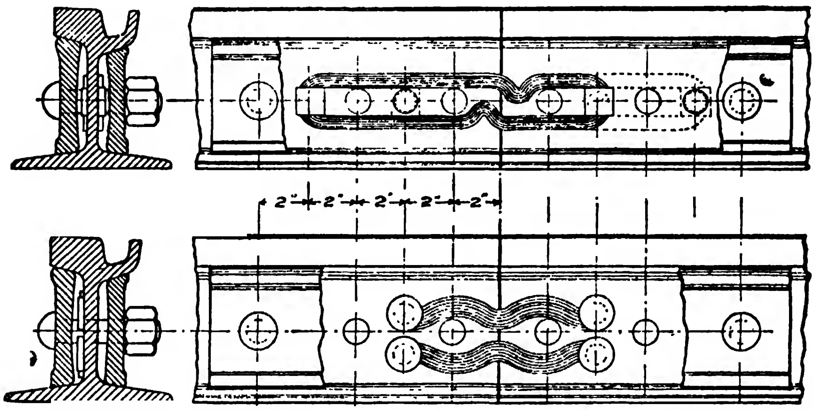


FIG. 395.—Location of 12 in. and 8 in. Protected Bonds on Tramway Rails.

being carried out. A typical bond in common use has a cross-section equivalent to 4/0 B. & S. gauge (0·166 sq. in.) and consists of 24 strands of flat copper wire (0·193 in. × 0·036 in.), with terminals $\frac{7}{8}$ in. in diameter by $\frac{3}{4}$ in. long, and shoulders (which are the thickest parts of the bond) $\frac{1}{2}$ in. thick. Two sizes are used in connection with standard rails, one (12 in. long) suitable for rail section No. 6, where only one bond can be placed on the same side of the web, and the other (8 in. long) suitable for rail sections Nos. 7 and 8, where two bonds may be placed on the same side of the web.

Bonding. The terminals of the bonds are expanded into the rail, under a pressure of 20 to 30 tons, by a screw or hydraulic press.

A typical **screw press** is shown in Fig. 396. The outer (square-threaded) screw, carrying the handwheel and hexagonal nut, is for clamping the press to the rail; the head of the press bearing against the shoulder of the bond, and the end of the screw against the web. The inner screw is for expanding the bond terminal, and the end in contact with the bond is pointed. When this screw is tightened, the bond terminal is expanded into the rail, and a button-head is formed on the terminal on the opposite side to the shoulder.

* *Journ. I.E.E.*, vol. 43, p. 464.

When welded rail joints are adopted, it is general practice to fix one bond over the joint in order to obtain increased conductivity.

In addition to bonds between the rail joints, the rails are **cross-bonded** at intervals of 40 yd., and on double track cross-bonds are fitted between the tracks at intervals of 80 to 100 yd. At junctions and special work, the rails should be bonded independently of the points and crossings. For these purposes bonds consisting of stranded cable, with forged copper terminals, are employed, the heads of which are expanded into holes in the rail.

Resistance of bonded joint. The **contact resistance** of a bond terminal in a rail is largely influenced by the state of the hole and the terminal at the time of bonding. In order to obtain the minimum contact resistance, it is necessary that the hole and the bond terminal be both clean, dry,

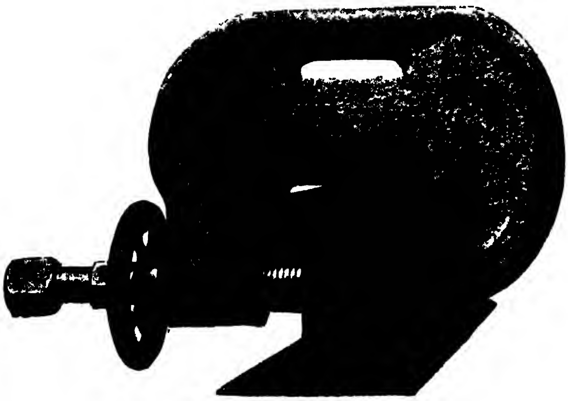


FIG. 396.—Method of Fixing Protected Bonds with Screw Press.

and bright. Tests have shown that the contact resistance of a $\frac{7}{8}$ in. terminal, in a rail with a web $\frac{1}{2}$ in. thick, may be as low as two microhms when the hole and bond are very clean. A thin film of oil or oxide on the bond or hole is sufficient to increase this resistance two to three times the original value. With fish-plates properly fitted, the resistance of a joint without bonds may be 20 microhms (or less), but this value will be considerably increased when any looseness occurs between the fish-plates and the rails. Taking the value of 20 microhms for the resistance of the fish-plate portion of the joint, the total resistance of a joint (for rails weighing 104 lb. per yard), bonded with two 8 in., 0·166 sq. in. bonds under the fish-plates, will be about 10 microhms,* which is equivalent to 15 in. of rail. If the contact resistance of the fish-plates increases, the resistance of the joint will increase, and would ultimately become (with infinite fish-plate resistance) 22 microhms, which is equivalent to 31 in. of rail.

* Obtained as follows: Conductor resistance of each bond = 38 microhms; contact resistances per bond (say), 7 microhms; resistance of two bonds fitted to rail, 22 microhms; combined resistance of bonds and fish-plates, 10·5 microhms (taking contact resistance of fish-plates as 20 microhms).

CHAPTER XXIII

Conductor Rails and Track-Work for Electric Railways

On electric railways the track rails in many cases are used as the return conductor.

The **bull-head** type of rail is used for the track by all the large railways in this country, while the Vignoles or flat-bottomed rail is generally used in America. Particulars of standard sections of bull-head rails are given in Table XVIII.

TABLE XVIII

Data of Standard Bull-head Railway Rails

B.S. section (indicating the weight in lb. per yard)	60	65	70	75	80	85	90	95	100
Height of rail (in.) .	$4\frac{3}{4}$	$4\frac{7}{8}$	5	$5\frac{1}{8}$	$5\frac{3}{8}$	$5\frac{17}{32}$	$5\frac{37}{64}$	$5\frac{23}{32}$	$5\frac{29}{32}$
Width of head (in.) .	$2\frac{5}{16}$	$2\frac{3}{8}$	$2\frac{7}{16}$	$2\frac{1}{2}$	$2\frac{9}{16}$	$2\frac{11}{16}$	$2\frac{3}{4}$	$2\frac{3}{4}$	$2\frac{3}{4}$
Thickness of web (in.) .	$\frac{17}{32}$	$\frac{9}{16}$	$\frac{19}{32}$	$\frac{5}{8}$	$\frac{21}{32}$	$\frac{11}{16}$	$\frac{3}{4}$	$\frac{3}{4}$	$\frac{3}{4}$
Cross-sectional area (sq. in.)	5·87	6·34	6·88	7·32	7·8	8·33	8·81	9·28	9·8
Perimeter (in.) . .	16·04	16·87	17·85	18·34	18·76	18·93	19·01	19·06	19·11

The **chemical composition** depends upon the process of steel manufacture and the carbon content. The limits for the impurities are—

Carbon .	0·4 to 0·65 per cent
Manganese	0·7 to 1·0 per cent
Silicon .	0·1 to 0·3 per cent
Phosphorus	0·04 to 0·075 per cent
Sulphur .	0·05 to 0·07 per cent

Several railways, however, have their own special composition for rails, and in many cases rails made by the Sandberg process are in use.

Where the track rails are used as the return conductor, the voltage drop in the rails is limited to 7 volts on systems operating with direct current, and to about 15 volts on systems operating with alternating current (since electrolytic effects are much smaller with alternating current than with continuous current). The track-rail joints are bonded in a manner similar to those on tramways, and cross-bonds are fixed between the rails, and also between the tracks, at frequent intervals. On alternating-current railways the rails are also bonded to the structures supporting the overhead conductors.

The ohmic resistance of steel rails to alternating current is much higher than the resistance to direct current, due to the non-uniform distribution of current through the cross-section in the former case. On account of the magnetic properties of the rail, the alternating current is practically confined to a thin surface layer of a few millimetres. In

addition to this increase of resistance, the magnetic properties of the rail considerably increase the inductance. If alternating-current traction were adopted on a large scale, it might be desirable to use a rail of poor magnetic quality, e.g. one containing a fairly high percentage of manganese. The increased cost of such a rail would have to be balanced against the decreased cost of feeders and the wearing qualities. The inductance and resistance of rails, and their influence on the design of feeders for alternating-current railways are treated in Chapter XXVI.

On direct-current railways the current is usually supplied to the trains through one or two **conductor rails,** the latter number being adopted when the track rails are not used as the return conductor. The wear on conductor rails is only that due to the friction of the collector shoes, and, as the strength of the rail is unimportant, the design, as far as the cost will permit, can be made from an electrical standpoint. The principal considerations, other than conductivity and cost, are: (1) the contact surface available for the collector shoes; (2) the shape of the section (with reference to installation and insulators); (3) the wearing qualities.

Steel is adopted for reasons of economy, and the composition is arranged so that the highest conductivity is obtained consistent with the above conditions. The **influence of the chemical composition** of iron and steel **on the electrical resistance** is shown in Table XIX.*

TABLE XIX

VARIATION OF RESISTANCE OF IRON AND STEEL WITH CHEMICAL COMPOSITION (J. A. CAPP)

Impurities.					Resistance relative to Copper.	Temperature.	Remarks.
Carbon.	Manganese.	Phosphorus	Silicon.	Sulphur.			
per cent.	per cent.	per cent	per cent.	per cent.		Deg. C.	
0·33	1·27	0·09	0·05	0·05	13·2	19	Track rails.
0·17	1·09	0·09	0·004	0·054	12·12	20	
0·22	1·08	0·1	0·05	0·05	11·51	20	
0·36	0·87	0·08	0·04	0·09	10·04	19	
0·144	0·46	0·09	Trace.	0·08	8·42	23·5	Conductor rails.
0·05	0·19	0·051	0·03	0·059	6·4	19	
0·16	0·074	0·12	0·1	0·027	7·41	26	Refined bar iron.
0·08	Nil.	0·13	0·024	0·008	7·11	25·5	Special refined bar iron.
0·17	0·027	0·074	0·077	0·022	6·76	25·5	
0·06	0·1	0·014	0·012	Trace.	6·17	24	Swedish iron.

Of the impurities usually found in steel, carbon and manganese have the greatest effect on the resistance. Considering pure iron, the addition of carbon increases the resistance fairly rapidly until 0·3 per cent of carbon is reached, after which the increase of resistance is practically proportional to the increase of carbon. Manganese has a much greater

* *Transactions of American Institute of Mining Engineers,* vol. 34, p. 400. Paper by J. A. Capp on "Tests of Steel for Electrical Conductivity." See also the investigations of Barrett, Brown, and Hadfield in the *Transactions of the Royal Society of Dublin,* vol. 7, Series 2, Part 4.

effect on the resistance than carbon, until about 10 per cent of manganese is reached, after which the addition of manganese has very little effect.

In practice, the steel used for conductor rails has a specific resistance

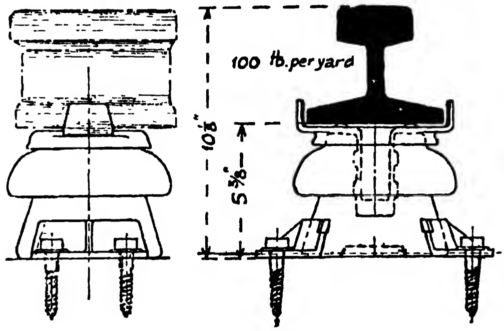
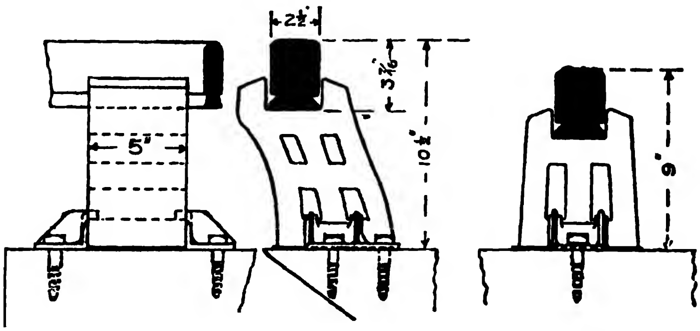


Fig. 397.—Method of Mounting "Vignoles" Type Conductor Rails.

of about seven times that of copper. Table XX gives data of the composition and resistance of conductor rails on various railways.

Classification of conductor rails. The conductor rails in general use may be divided into three classes according to the position of the contact



Positive Rail and Insulator. Negative Rail and Insulator.

Fig. 398.—Method of Mounting "Solid" Type Conductor Rails.

surface. For instance, the contact surface may be at the top, bottom, or side of the rail. Hence the classification of the rails becomes: (1) top-contact rails, (2) under-contact rails, (3) side-contact rails.

The top-contact rail is adopted universally for low-voltage (600 volts) electrifications in this country. The side-contact rail was developed for the 1200-volt electrification of the Manchester–Bury section of the London, Midland and Scottish Railway. The under-contact rail is adopted in America for both high- and low-voltage lines. One advantage of this type of rail is that the contact surface is protected from snow, sleet, and ice.

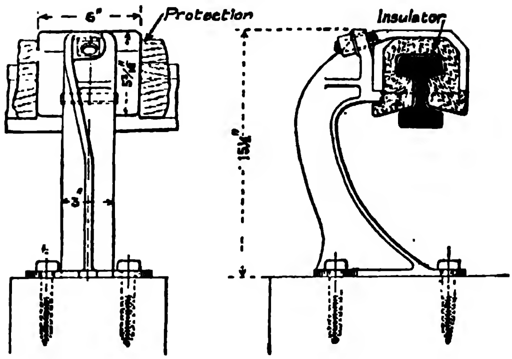


FIG. 399.—Method of Mounting Under-contact Conductor Rails.

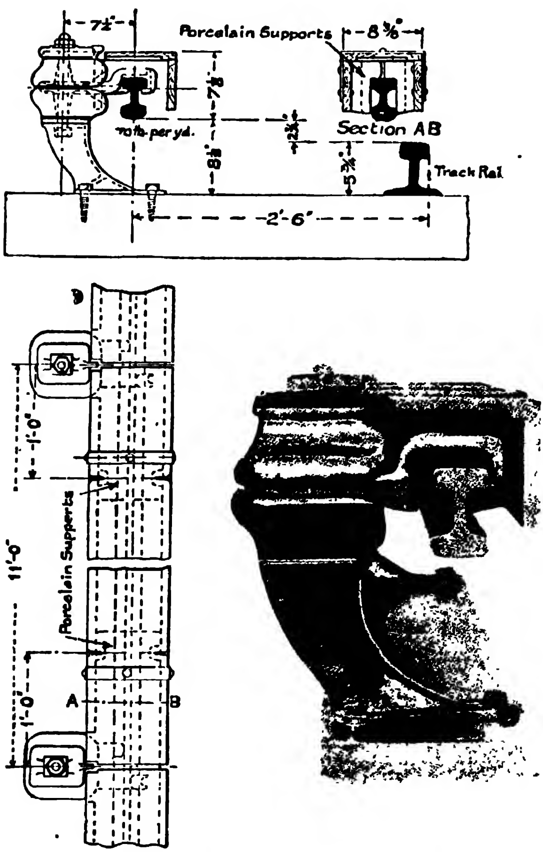


FIG. 400.—General Electric Under-contact Conductor Rail for 2400 Volts.

The **type of section** adopted for top-contact conductor rails is usually the Vignoles or flat-bottomed section, although channel and special rectangular sections have been used in some installations. The conductor rails for the early electric railways were of channel section, and were very light in weight, the original conductor rail (installed in 1890) on the City and South London (Tube) Railway weighing only 10 lb. per yard. The conditions of modern traffic, however, require a much heavier rail, and sections weighing 100 lb. per yard are generally used for urban and suburban railways.

A bull-head section is employed for under-contact rails, and a special angle section for side-contact rails.

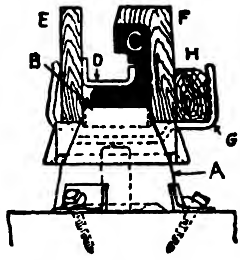


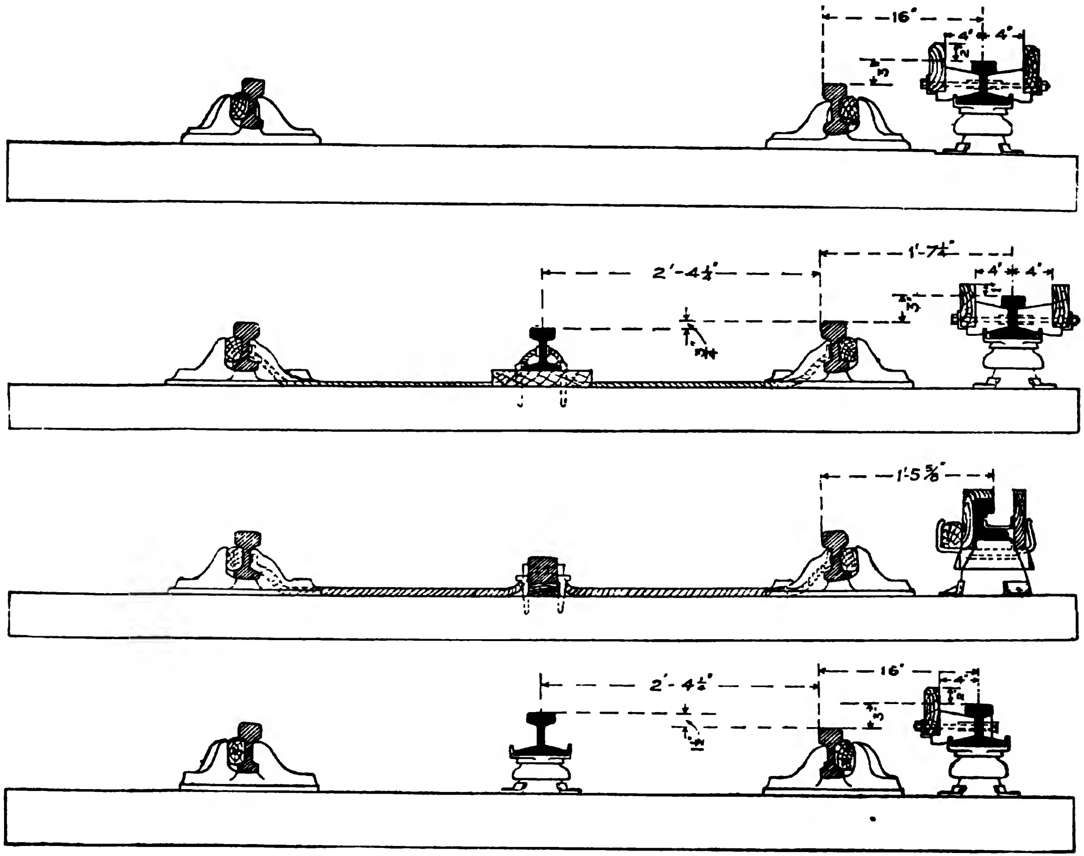
Fig. 401.—Aspinall Side-contact Conductor Rail for 1200 Volts.

Mounting. Methods of mounting typical low-voltage conductor rails and insulators are shown in Figs. 397–9. Fig. 397 shows the type of rail and insulator which has been standardized for low-voltage electrifications in this country. The rail (which usually weighs 100 lb. per yard) rests on a malleable-iron cap which is fixed to the top of a petticoated "pedestal type" porcelain insulator, the base of which rests directly upon one of the sleepers carrying the track rails, and is secured in position by two


Fig. 402.—Double Track equipped with Aspinall Side-contact, 1200-volt, Conductor Rails (Lancashire and Yorkshire Railway).

malleable-iron clamps. The insulator is a considerable improvement over the earlier types with metal bases, as the whole distance between the sleeper and the conductor rail is utilized for insulation, thereby obtaining a maximum length of leakage path. The wide petticoat is also advantageous in keeping the lower part of the insulator dry.

Fig. 398 shows the type of conductor rail and tubular earthenware insulator in use on the tube railways of the London Electric Railways. The difference in the shape of the insulators for the positive and negative



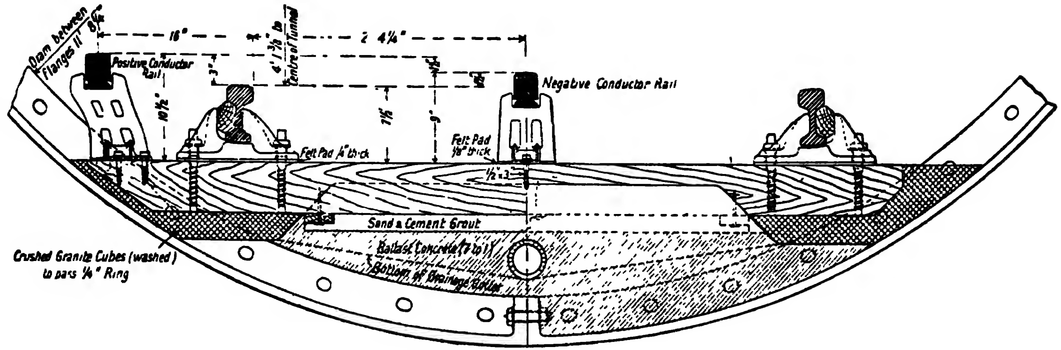
A

B

C

D

E



F

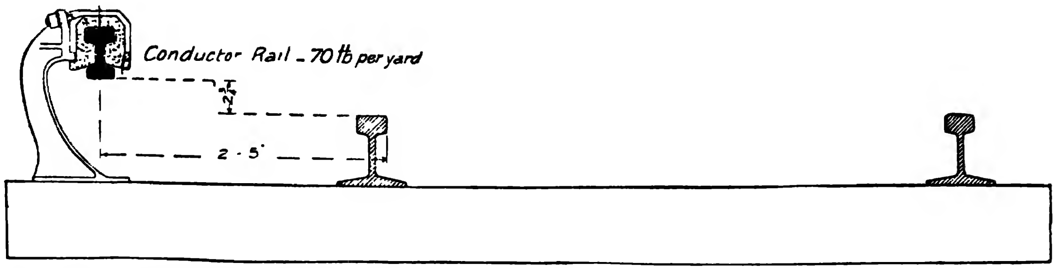


FIG. 403.—Cross-sections of Single-track, showing Location of Conductor Rails. *A*, Southern Rly.; *B*, *C*, London, Midland & Scottish Rly. (*B*, Lancashire 600-V. lines; *C*, 1200-V. Lines); *D*, Metropolitan and District Rlys, and London, Midland & Scottish Rly. (London Lines); *E*, London Electric (Tube) Rlys.; *F*, New York Central Rly.

conductor rails is due to the short length of the sleepers. The location of the insulators and conductor rails with respect to the track rails can be seen in Figs. 403, 406.

The method of mounting low-voltage, under-contact conductor rails is shown in Fig. 399. The rail is supported from cast-iron brackets (fixed to the sleepers) by means of special porcelain insulators, which are in halves and are held in position by a hook bolt. The portion of the rail between the insulators is protected by either wooden or fibre protection, so that only the lower (or contact) surface of the rail is exposed.

Conductor rails for high-voltage circuits. When conductor rails are to be used on high-voltage circuits, the insulation and protection of the rail must be given special consideration. As far as protection is concerned, the under-contact and side-contact types possess advantages over the top-contact type.

The **high-voltage, under-contact rail,** illustrated in Fig. 400, was developed by the General Electric Company for 2400-volt circuits. The general features of the low-voltage type have been retained, but the insulation and protection have been modified. The conductor rail (of bull-head section) is held in special clips, which are fixed between two insulators in the manner shown in Fig. 400. The protection consists of an inverted trough of wood, which is maintained in position on the conductor rail by means of porcelain distance pieces.

The **side-contact type** of conductor rail is due to Sir John Aspinall, and is installed on the Manchester-Bury (1200-volt) section of the London, Midland and Scottish Railway. A drawing of the rail, showing the protection and method of mounting, is given in Fig. 401,* and a view of the track equipped with this type of rail is shown in Fig. 402.*

Referring to Fig. 401, the conductor rail *C* (which weighs 85 lb. per yard) rests upon a block of wood *B*, located in a recess formed in the top of the porcelain insulator *A*. The latter is of the pedestal type, and is fixed to the sleeper in the usual manner. The two wooden protecting guards, *E*, *F*, project 1 in. below the flange of the conductor rail, and thus prevent the possibility of the permanent-way staff coming into contact with the underside of the rail. This projection of the guards below the flange of conductor rail also prevents transverse movements of the latter.

Attention must be directed to the shape of the inner protecting guard *F*. This guard is sawn out of the solid in order to avoid the possibility of any nails or screws coming into contact with the conductor rail.

The protecting guards rest upon ledges formed on the insulator, while the guards and the conductor rail are maintained in their correct positions by means of distance pieces *D*, spring clips *G*, and keys *H* (which are standard permanent-way keys). The distance pieces *D* are placed at intervals where it is found that they are necessary. In this manner a space ½ in. wide is obtained between the flange of the conductor rail and the outer protecting guard, so that no accumulation of water can occur inside the guards.

The **positions of the conductor rails** with respect to the track rails will depend on the type of conductor rail and the rolling-stock gauge.

* See Fig. 238 for view of the collector shoe.

In this country the following standard positions have been adopted for top-contact conductor rails—

(*a*) When the conductor rail is located between the track rails: centre-line of conductor rail to coincide with the centre-line of the track rails, and the top of the conductor rail to be 1½ in. above the top of track rails.

(*b*) When the conductor rail is located outside the track rails: centre-line of conductor rail to be 1 ft. 7¼ in.* from gauge line of nearest track rail, and the top of conductor rail to be 3 in. above the top of track rails.

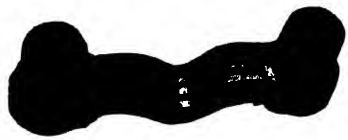


Fig. 404.—Flexible Bond for Conductor Rails.

Cross-sections of single track for typical electric railways are given in Fig. 403. In these diagrams the protection of the rail at stations is also shown, this protection (for top-contact rails) being in the form of wooden boards fixed on each side of the conductor rail. The track rails form the return in examples *A*, *B*, *C*, *F*. In cases *B*, *C*, they are supplemented by uninsulated conductors which are bonded to the track rails. The

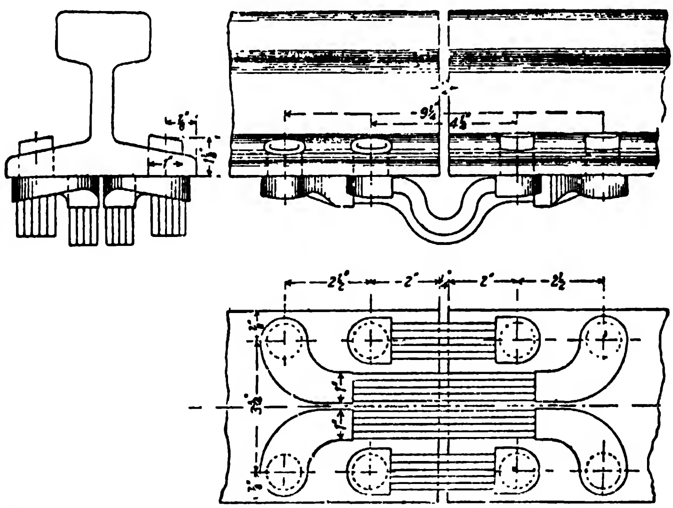


Fig. 405.—Bonding for 100-lb. Conductor Rails. Note.—Each bond has a cross-section of 0·35 sq. in.

square cross-section in example *C* was adopted in order to reduce the area exposed to the atmosphere, and therefore minimize corrosion.†

Bonding of conductor rails. As the conductor rails are used solely as electrical conductors, and on a large system may have to carry currents of 2000 amperes for short periods, it is necessary to bond the joints to the full current-carrying capacity of the rail. The bonds are similar in type to those used on tramways. but are flexible, shorter, and of larger cross-section.

* This dimension is 16 in. for the London Railways.

† The corrosion of conductor rails is considerably greater than that of track rails See Sir John Aspinall's Presidential Address, *Proc. I.M.E.*, p. 436.

Fig. 406.—Cross over on London Tube Railway, showing Location of Positive and Negative Conductor Rails. At *A* is shown a cable terminal plate. Note—The train consists of three coaches—one motor coach (at rear) and two trailer coaches. The vestibule of the leading (trailer) coach is arranged for driving, and is provided with a master controller, brake valve, and control-circuit switches.

A typical bond (for the Vignoles type of rail) is shown in Fig. 404, and a drawing showing the bonding for a 100 lb. conductor rail is given in Fig. 405. The bonds shown in these illustrations have solid heads, which are expanded into the rail by a hydraulic press. In some cases, however, bonds with hollow heads are employed, which are expanded into the rail by drift pins.*

Feeder cables (and jumper cables) may be connected to the conductor rails by means of either several bonds with cable sockets, or a special

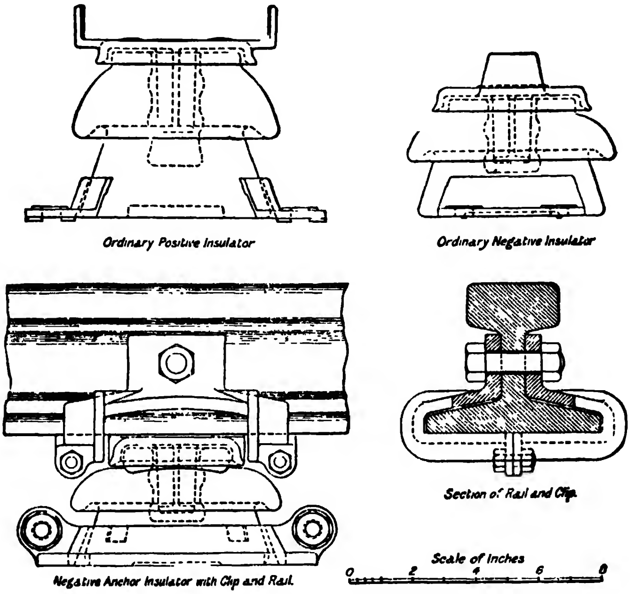


Fig. 407.—Detail of Doulton's Conductor Rail Insulators, and Method of Anchoring Conductor Rail.

copper plate (which is provided with cable sockets) bolted to the web of the rail. An example of the latter method is shown at *A* in Fig. 406.

At **cross-overs and special track-work** it is necessary to insert gaps in the conductor rails. The continuity of the various conductor rails of similar polarity is maintained by jumper cables.

In Fig. 406 is shown a view of the conductor rails at a cross-over road. It will be observed that the ends of the conductor rails are formed into ramps, by means of which the collector shoes are prevented from fouling when a train is passing over the special track-work.

In order that the supply of current to the train shall not be interrupted when it is passing over special track-work, the distance apart of the front and rear collector shoes must be greater than the longest gap in the conductor rails. In some cases (for example, in locomotives, single motor coaches, and motor-coach trains for tube railways, where no " bus lines " are allowed on the train) it will not be possible to fulfi

* " Electrical Equipment of Track on the Underground Railways of London," paper by Mr. A. R. Cooper, *Journ. I.E.E.*, vol. 65, p. 389.

this requirement, and under these circumstances the train will have to coast over the gap.

At large freight yards it will not be possible to install conductor rails, as, in addition to the complication to the track and the danger to the shunters, the lengths of the gaps would be too great to be bridged by the collector shoes on a locomotive, and in shunting operations it is essential that the locomotive should be able to obtain current at any position. Overhead work must therefore be erected at these places, and the locomotive must be equipped with a bow collector.

The conductor rails are divided into **sections** of convenient length, and the section insulators are usually arranged near the sub-stations. (The feeding and switching arrangements for the conductor rails and section insulators are discussed in Chapter XXVI.) Each section is anchored at one point, either by bolting to the rail a special anchor clip and anchoring one of the insulators, as shown in Fig. 407,* or by means of insulated anchor ties.

* Messrs. Doulton & Co. (to whom the author is indebted for Fig. 407) have informed the author that the type of anchor insulator illustrated, and the method of anchoring to the sleeper, are covered by their patent, but the special rail clips used in conjunction with the anchor insulators are covered by the patent of Mr. H. Scott, of the London, Midland and Scottish Railway. The method of anchoring has also been adopted on the Southern Railway.

TABLE XX

Chemical Composition, Resistance, and Data of Conductor Rails on British Railways

Railway	Impurities.					Ratio of Spec. Res. of Rail to Spec. Res. of Copper at 20° C.	Weight	Cross-sectional Area	Width of Head at Contact Surface	Total Cross-section of Bonds per Joint
	Carbon	Man-ganese	Phos-phorus	Silicon	Sulphur					
	Per cent	Per cent	Per cent	Per cent	Per cent		lb. per yard	sq. in.	in.	sq. in.
London and North Eastern . . .	0·05	0·4	0·1	0·2	0·08	7·25	80	7·83	2½	0·66
Metropolitan District (London) . .	0·035	0·315	0·056	Nil	0·059	6·5	100	9·8	2¼	1·4
London, Midland & Scottish (600-V. lines, London)*	0·044	0·139	0·011	0·03	0·029	6·5	105	10·4	2⅞	1·4
London, Midland & Scottish (600-V. lines, Lancashire)	0·045	0·23	0·046	Trace	0·04	7·23	70	6·86	2½	0·66
London, Midland & Scottish (1200-V. lines)	0·08	0·22	0·034	0·022	0·026	6·75	85	8·5	1⅝	0·8
Southern	0·047	0·34	0·053	Trace	0·055	6·75	100	9·8	2¼	1·4
London Electric (Tube) Railways . .	0·05	0·19	0·05	0·03	0·05	6·4	85	8·37	2½	1·33

* This conductor rail contains 0·255 per cent nickel.

CHAPTER XXIV

OVERHEAD CONSTRUCTION FOR TRAMWAYS AND TROLLEY-OMNIBUS ROUTES

OVERHEAD construction has been standardized for a number of years, and modern installations show only improvements in a few details. Statutory regulations require the trolley wire to be erected at a minimum height of 17 ft. above the street surface (except under bridges), and to be supported at intervals not greater than 120 ft. Further, each trolley wire must be divided into sections, not exceeding one-half of a mile in length, with an emergency switch between every two sections.

In addition to satisfying these requirements, the trolley wire must be designed to fulfil its function as an electrical conductor and to withstand the mechanical stresses due to temperature variation, etc.

Trolley wire. The **material** in general use is hard-drawn copper, but alloyed wire has better wearing qualities, owing to its being uniformly hard throughout, whereas, with hard-drawn copper wire the hardness is confined to the outer skin. The chief objection to alloyed wire is its high specific resistance, which exceeds twice that of copper.

The chief mechanical and electrical properties of copper and alloyed wire are—

	Hard-drawn copper wire	Alloyed (phono-electric) wire
Ultimate tensile strength (tons per sq. in.)	23 to 26	31 to 35
Elastic limit (tons per sq. in.)	7·5 to 12·5	24 to 25
Young's modulus of elasticity (lb. per sq. in.)	18×10^6	$18{\cdot}14 \times 10^6$
Specific resistance (60° F.) (ohm per in. cube)	$0{\cdot}69 \times 10^{-6}$	$1{\cdot}61 \times 10^{-6}$

The **form of cross-section** is either circular or grooved circular (Fig. 409). Grooved wire is employed exclusively in all modern installations owing to its advantages over plain circular wire. Thus, (1) soldering during erection is eliminated, as all suspension fittings are fastened by clips; (2) smoother running of the trolley wheel is obtained, owing to the clipped fittings offering less obstruction than soldered fittings; and (3) the grooved wire can be erected quicker than circular wire.

Support of trolley wire. The trolley wire is supported and insulated from a transverse span wire by means of a steel bolt screwed into a gun-metal ear attached to the trolley wire, the bolt being insulated from, and held in, a hanger attached to the span wire. The span wire is supported from poles and is insulated therefrom. There is, therefore, double insulation between the trolley wire and earth.

Various types of ears are illustrated in Fig. 408.

The suspension bolts are of two standard sizes, viz. $\frac{5}{8}$ in. and $\frac{3}{4}$ in. Formerly they were of the insulated type, the head and body being insulated with moulded insulation to standard overall dimensions, to

fit uninsulated gun-metal or malleable-iron hangers. Present-day practice favours the use of uninsulated sherardized bolts and insulated hangers with porcelain insulation.

Alternatively, the ears may be bolted directly to the hangers (by uninsulated bolts), and the latter insulated from the poles and span wires by a double set of porcelain strain insulators.

A further method (which has been introduced for trolley-bus routes)

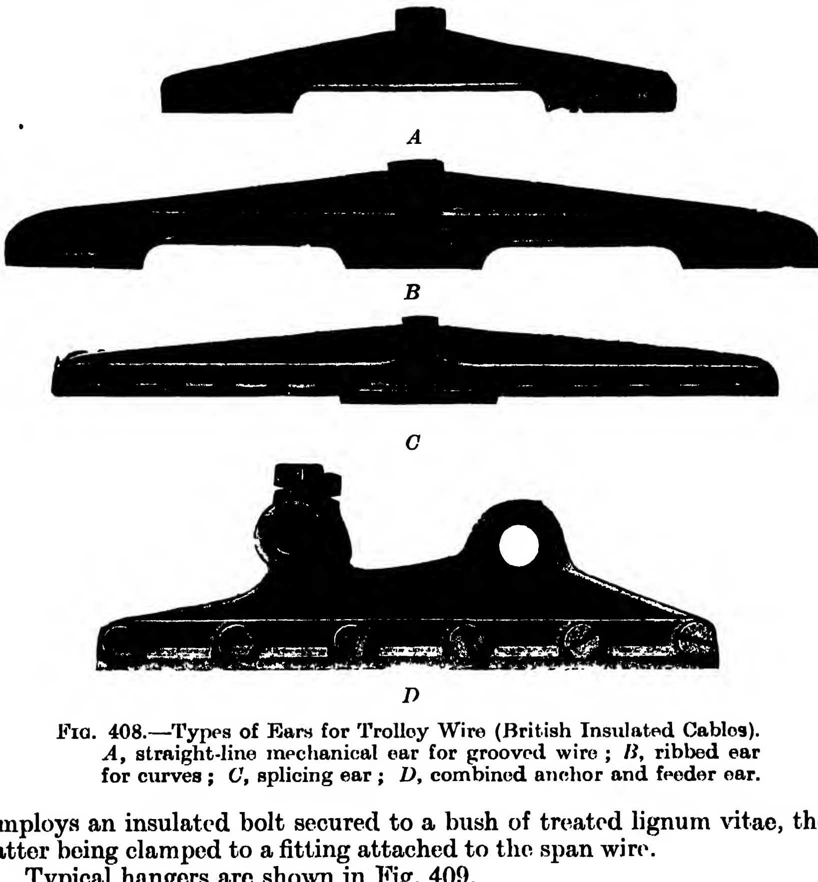


Fig. 408.—Types of Ears for Trolley Wire (British Insulated Cables). *A*, straight-line mechanical ear for grooved wire ; *B*, ribbed ear for curves ; *C*, splicing ear ; *D*, combined anchor and feeder ear.

employs an insulated bolt secured to a bush of treated lignum vitae, the latter being clamped to a fitting attached to the span wire.

Typical hangers are shown in Fig. 409.

On straight track the span wire supporting the hanger is above the level of the trolley wire, but at curved track the span wire must be on a level with the trolley wire, otherwise the hanger will be pulled out of the vertical. Hangers for curves are called "**pull-offs,**" the double pull-off being used when both sides of the span wire are in tension.

The **span wire** is of stranded galvanized or sherardized steel, having an ultimate tensile strength of 29 tons per sq. in., and an elastic limit of 20 tons per sq. in. The sizes in common use are 7/·125″, 7/·104″, and 7/·083″, for which the average breaking loads are 4550 lb., 3950 lb., and 2400 lb. respectively.

The wire may extend the whole width of the road (in which case it is

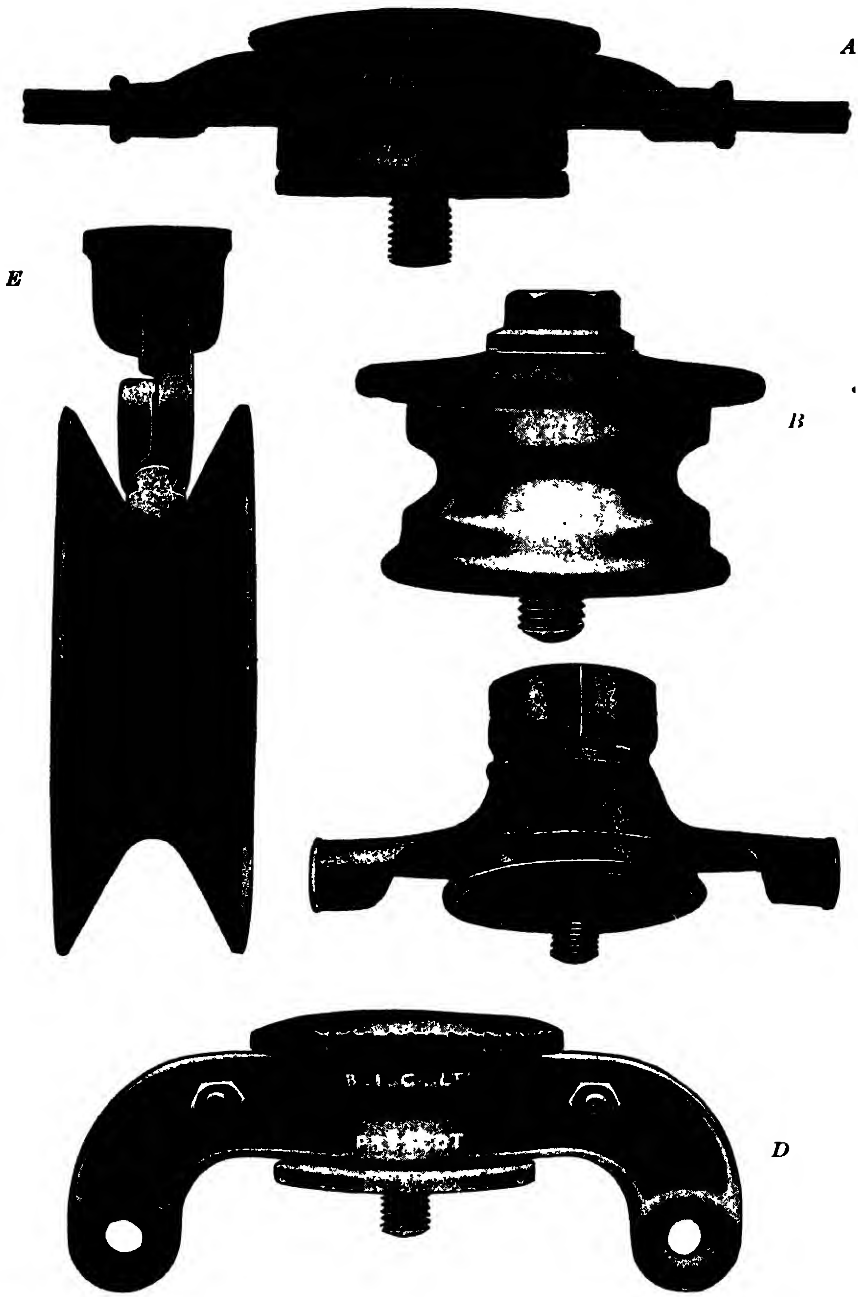


Fig. 409.—Types of Hangers (British Insulated Cables). *A*, straight-line hanger (complete with porcelain insulator and screwed-in bolt) in position on span wire; *B*, porcelain body of hanger with loose bolt; *C*, straight-line hanger (old type) with insulated bolt; *D*, double pull-off with porcelain insulator; *E*, Municipal Tramways Association's standard form of trolley wire, ear, and trolley wheel.

attached to poles on each side of the road), or a short length of span wire carrying the hanger may be attached to brackets carried from poles at the side or the centre of the tracks. These types of construction are known as span wire, side pole, and centre pole. The first two are the more common, as centre-pole construction is only adapted for wide streets or private right-of-way.

Side-pole construction is generally used with single track, and with double track in narrow streets. The maximum length of the bracket arm is 16 ft., which allows the trolley wire to be fixed at a maximum distance of about 14 ft. from the kerb. A swivelling trolley head allows satisfactory operation to be obtained with the trolley wire 6 ft. from the centre of the track, and, under these conditions, the centre of the track can be 20 ft. from the kerb. By working to these extreme limits this construction could be used with double track in streets 32 ft. wide, and with single track in streets 40 ft. wide. It is not always desirable, however, to work to these limits, and span-wire construction is frequently adopted in streets below 30 ft. in width.

Span-wire construction is suitable for double track in any width of street, and is the only type of construction in use on some of the large tramway systems.

The **span-wire insulators** formerly consisted of moulded material (consisting of asbestos, powdered mica, shellac, etc., compressed at a high temperature to the required shape), but porcelain is the only material employed in many modern installations. The attachment of the span wire to the insulators must be so arranged that the insulation is subjected only to compressive stress.

Typical insulators are shown in Fig. 410. The composite "globe" insulator (manufactured by the Ohio Brass Co.) represents the latest development in moulded insulators. The strain is carried by two malleable iron castings, one of which is compressed over the other. The insulation between the castings consists of mica. Composition insulation is moulded around the central portion of the castings to protect the mica insulation from the weather and to increase the leakage surface. The moulded insulation is securely locked in position by the cup-shaped flanges formed near the eyes of the castings. A typical insulator of $2\frac{3}{4}$ in. in diameter has an average ultimate mechanical strength of 9000 lb., and a breakdown voltage, when dry, of about 14,000 volts. Corresponding values for the $4\frac{3}{8}$ in. $\times$ $2\frac{3}{8}$ in. size of porcelain loop insulator (*B*) are 10,000 lb. and 30,000 volts; and those for the 3 in. $\times$ 3 in. size of porcelain link insulator (*C*) are 6000 lb. and 30,000 volts.

Examples of bracket-arm and span-wire construction for straight track are shown in Fig. 411. In all cases of bracket-arm construction the trolley wire is flexibly supported from the bracket arm. This feature (i.e. flexible suspension) is essential in all overhead construction for tramways and railways, as any rigid parts of the trolley wire will be subjected to hammering from the collector, thereby causing sparking and excessive wear.

Construction at curves. At curved track the trolley wire is maintained in position by means of pull-off wires. As the tension in some cases may be considerable, strain insulators must be employed for insulating the

pull-off wires from the poles. The adjustment of the position of the trolley wire is effected by turnbuckles. (Formerly adjustable moulded strain insulators, called " Brooklyns," were employed.)

The **position of the trolley wire** relative to the track depends on the type of car, length and elevation of trolley pole, super-elevation of track, etc. The ideal position can be obtained from a track plan by using a plan of the car wheel base and trolley pole as a template (as indicated in Fig. 412), allowing for super-elevation of the track when necessary. In practice, this position of the trolley wire would require the use of too many pull-off wires, and it is approximated by a number of straight sections, with the angle between sections limited to a minimum of about

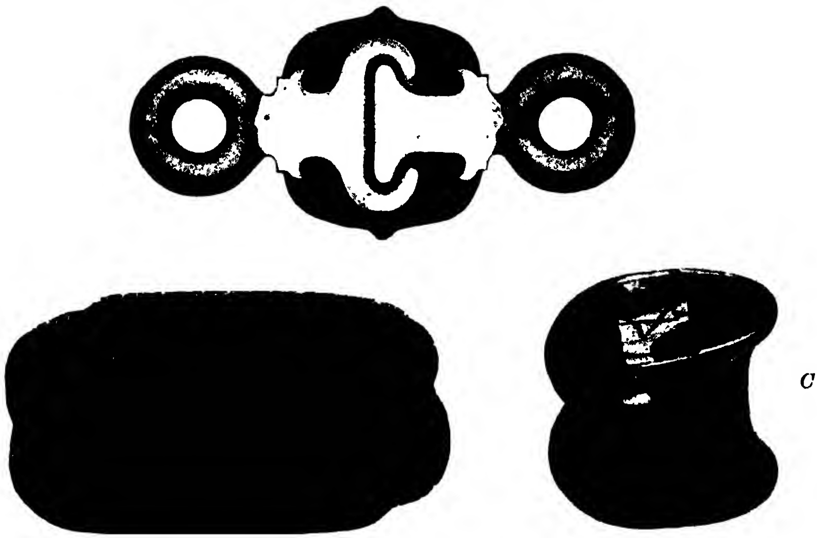


FIG. 410.—Types of Strain Insulators. *A*, " O.-B." globe; *B*, Prescot porcelain loop-type insulator; *C*, porcelain link-type insulator.

160 degrees, in order to avoid too sudden a change in the direction of motion of the trolley head. This point is of special importance, as sudden changes in the direction of motion of the trolley head not only cause excessive wear on the wire, but also increase the risk of the trolley wheel leaving the wire. The cars used on curves should, therefore, be longer and stronger than those on straight track.

The general practice relative to the **number of pull-offs on right-angle curves** is to install seven on curves of small radius (50 ft.) and nine or more on curves of larger radius.

With curves of very large radius, where the distance apart of the pull-offs may be from 50 to 60 ft., the pull-off wire is usually attached to a bridle between adjacent poles.

Fig. 412 is a diagram of the **overhead construction at a double-track right-angle curve.** This diagram shows the arrangement of the pull-off wires and the method of anchoring the straight lengths of trolley wire so as to render the straight sections and curves mutually independent

Hence, if an accident occurs on one of the straight sections, its effects are not transmitted to the curve.

Special fittings. At junctions, frogs and crossings are necessary for the guidance of the trolley wheel. **Frogs** are of two types, one being fitted with a movable tongue—for use at facing points—whilst the other

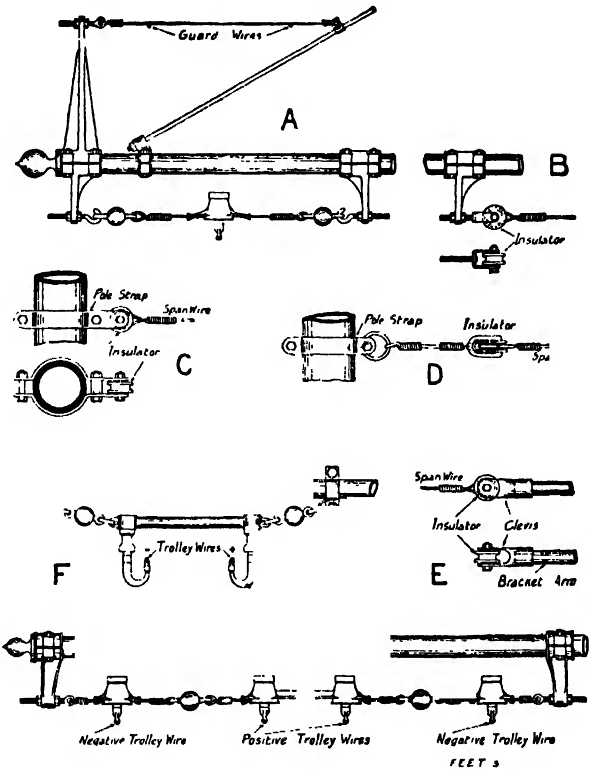


FIG. 411. - Examples of Overhead Construction. *A*, side-pole construction using "globe" insulators; *B*, side-pole construction using porcelain insulators; *C*, *D*, *E*, span-wire construction using porcelain insulators; *F*, construction for railless traction (over-running trolley system); *G*. construction for railless traction (under-running trolley system).

is without a tongue and is intended for trailing use only. A **two-way switch frog** is shown in Fig. 413. The tongue is maintained in one position by a spring, and is moved to the other position by a wire operated by the point controller or pointsman.

An **automatic frog** is shown in Fig. 414. In this frog (which can be used either for facing or trailing positions) the tongue is set, for the branch line, by the trolley pole engaging the weighted lever (at the side of the frog), and is returned to its normal position when this lever is released. For satisfactory operation the frog must be fixed so that,

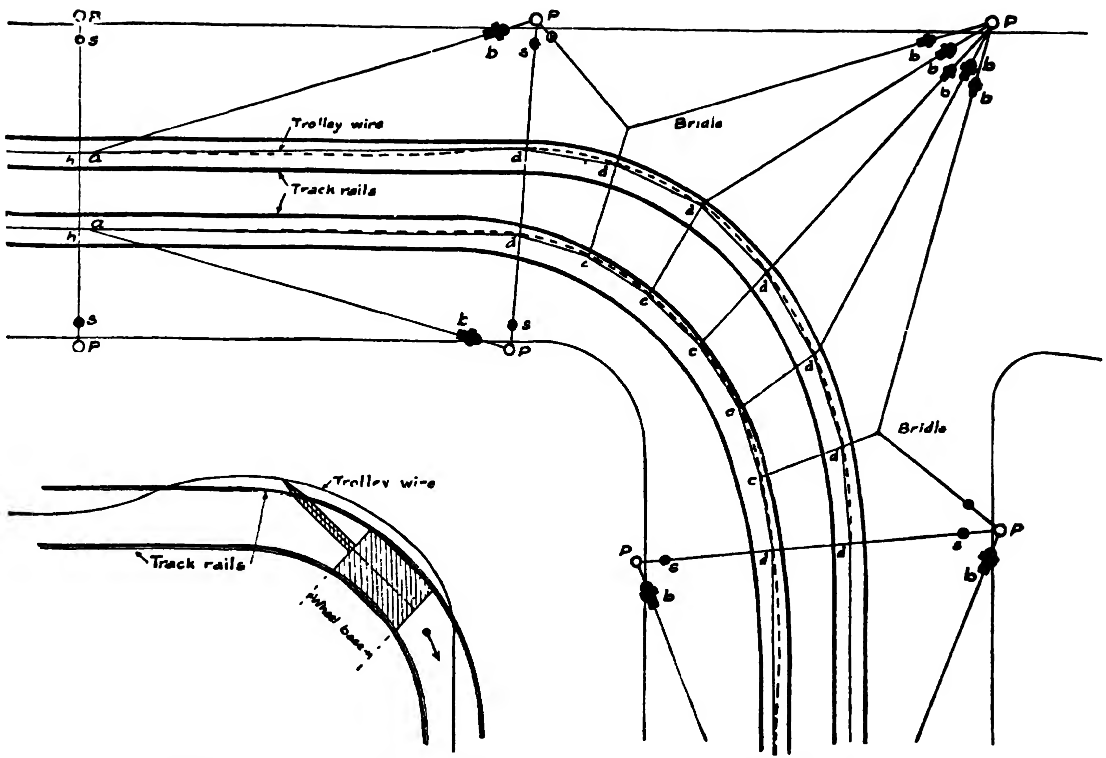


FIG. 412.—Diagram of Overhead Construction at a Double-track, Right-angle Curve. *a*, anchor ear; *b*, adjustable strain insulator (e.g. porcelain strain insulator and turnbuckle); *c*, single pull-off; *d*, double pull-off; *h*, straight-line ear; *s*, porcelain strain insulator; *P*, pole.

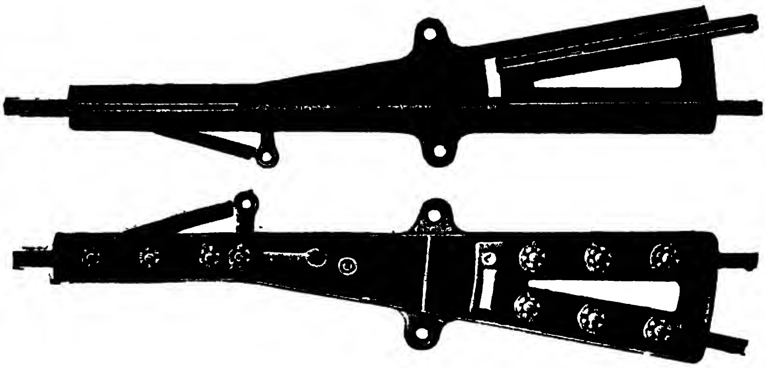


FIG. 413.—Switch Frog for Grooved Trolley Wire (British Insulated Cables).

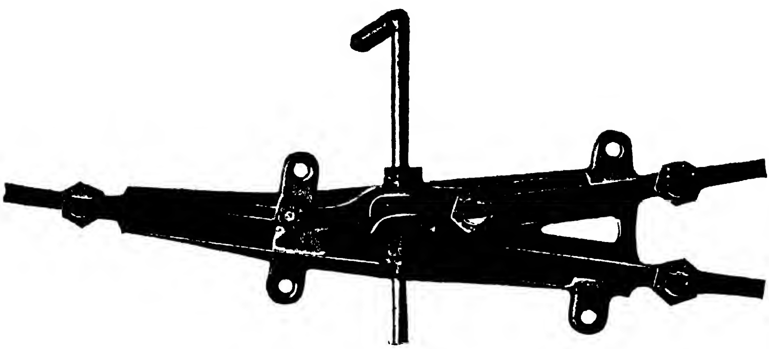


FIG. 414.—Automatic Frog—operated by Trolley Boom (British Insulated Cables).

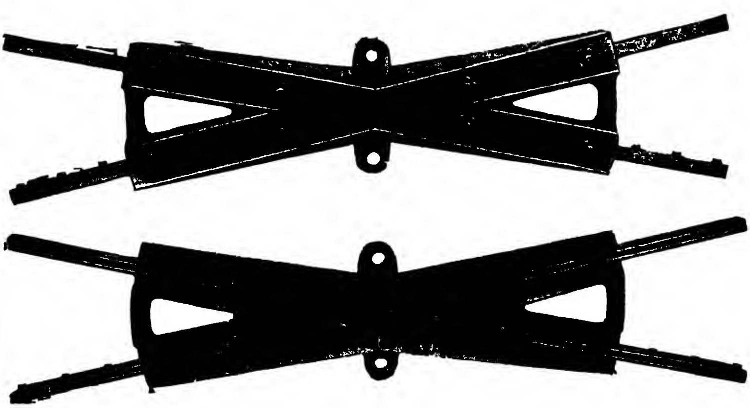


FIG. 415.—25 degrees Fixed Crossing (British Insulated Cables).

when a car is travelling on the branch line, the trolley wheel is on the frog when the trolley pole is making an angle of between 15 and 20 degrees (horizontally) with the main trolley wire.

A **crossing** is shown in Fig. 415. The grooves in the latter are for guiding the flanges of the trolley wheel.

A **section insulator** is shown in Fig. 416. The central section B is insulated from the end sections A. C (to which the trolley wires are

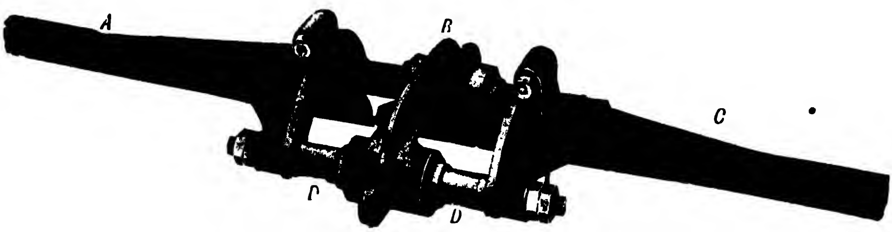


Fig. 416.—Section Insulator (Brecknell, Munro, and Rogers).

attached), and the principal strain is taken by the insulated bolts D, which are in the same horizontal plane as the trolley wire.

Views of section insulators erected are shown in Fig. 417, in which the cables leading to the switch pillar can be seen, and also the anchoring of the trolley wire on each side of the section insulator.

A diagram of the **overhead construction at a junction,** showing the arrangement of frogs, crossings, and section insulators, is given in Fig. 418.

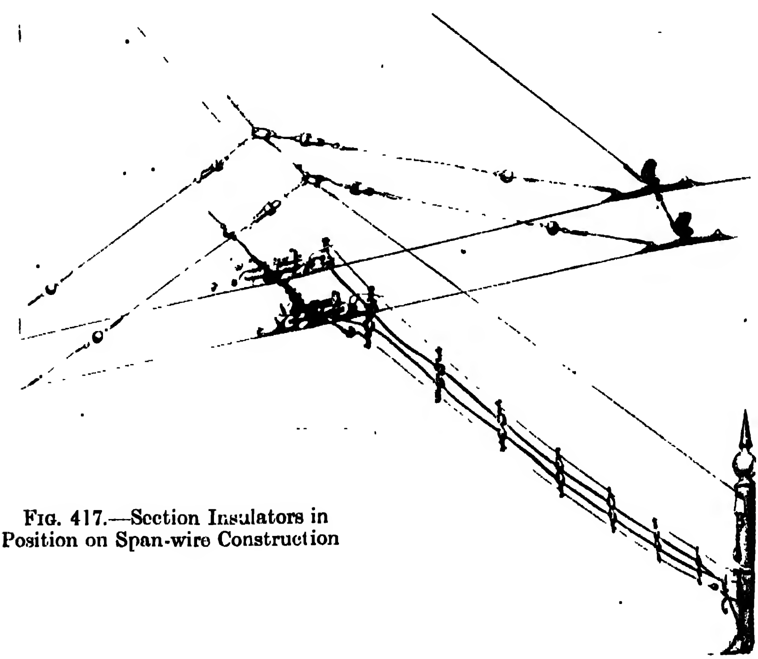


Fig. 417.—Section Insulators in Position on Span-wire Construction

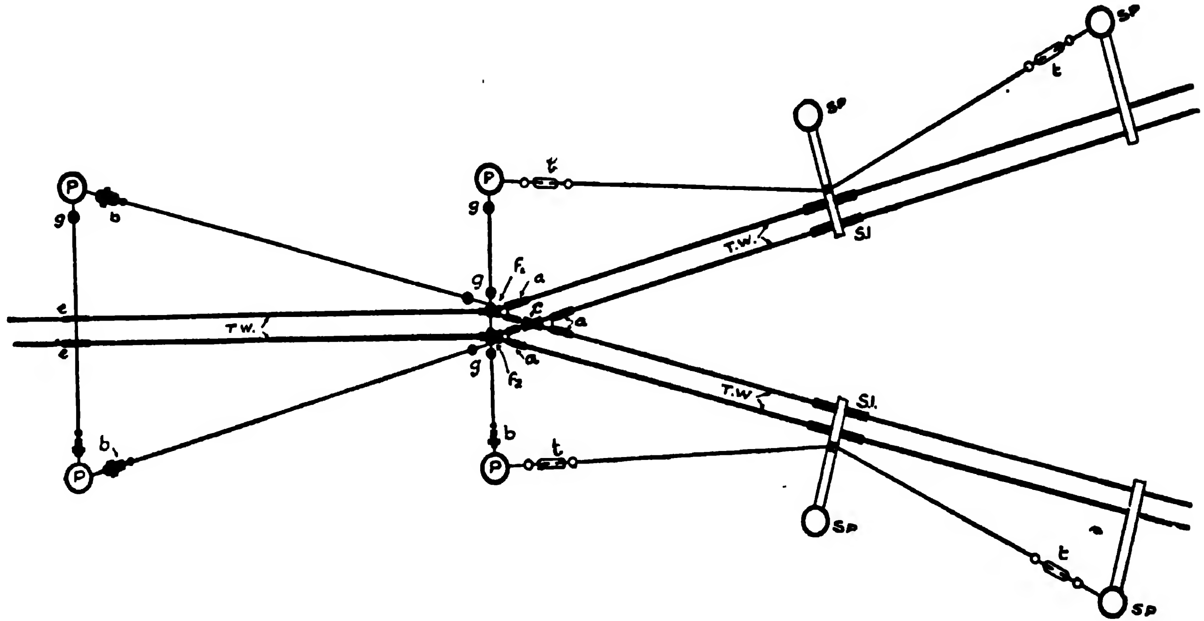


FIG. 418.—Diagram of Overhead Construction at Double-track Junction. *a*, special ears fitted with distance pieces to maintain trolley wires in correct relative positions ; *b*, adjustable strain insulator ; *c*, crossing ; *e*, straight-line ear : f_1, switch frog ; f_2, trailing frog ; *g*, non-adjustable strain insulator ; *t*, turnbuckle ; *P*, pole ; *SP*, side pole with bracket arm ; *SI*, section insulator.

The section insulators for the branch lines are carried on bracket arms which are anchored to poles on each side.

The overhead construction at junctions on **trolley-bus routes** differs from that at similar junctions on tramway routes as the trolley wires of opposite polarity must be insulated from each other at the crossings. Section insulators must, therefore, be inserted at these points. A special form of section insulator has been developed for this purpose, and is provided with special ends so as to fit directly into the ends of the appropriate frogs or crossings (which are of the standard type).

Where bare telephone and telegraph wires cross the trolley wires, **guard wires** have to be erected, as detailed on p. 693.

Poles. These are of the tubular type, and usually consist of three steel tubes, of different diameters, shrunk together with telescopic joints. The overall length is 31 ft.; the length of bottom section is 17 ft.; the middle and top sections are each 8 ft. 6 in. long; and each joint is 1 ft. 6 in. long. Three standard sizes are in use, viz. (1) "light," suitable for pulls up to 750 lb.; (2) "medium," suitable for pulls up to 1250 lb.; and (3) "heavy," suitable for pulls up to 2000 lb. The "heavy" poles are only used for anchoring purposes or at curves where several pull-off wires are attached to one pole.

The **pole trimmings** usually consist of a finial, fitted into the top of the pole; two collars, slipped over the joints; and a base, ornamented to suit the requirements of the neighbourhood. The **bracket arms** of side poles consist of steel tubing, $2\frac{1}{2}$ to 3 in. in diameter, fixed to the poles by means of collars and tie rods. On span-wire construction it is usual to use a short bracket arm of the type shown in Fig. 411 (*E*).

The poles are fixed in 6 ft. of concrete, with a concrete "biscuit" 6 in. thick under the base. The thickness of concrete around the pole depends on the nature of the subsoil, and under normal conditions about 8 to 10 in. is sufficient. Each pole is set with sufficient rake so that the tension in the span wire will pull it vertical.

Calculation of Stresses in Trolley Wire and Span Wires

Relationship between sag and tension for a trolley wire. A flexible wire, suspended horizontally and loaded only by its own weight, hangs in the form of a catenary.* But if the sag is small in comparison with the span the catenary is practically identical with a parabola.† With tramway overhead construction, the sag in the trolley wire rarely exceeds

* The general equation of the catenary is—

$$y = \tfrac{1}{2}a\,(\epsilon^{x/a} + \epsilon^{-x/a}) = a \cosh x/a,$$

where a is the distance from the origin to the vertex.

If z is the height of the point x, y, above the vertex (Fig. 419), then

$$z = y - a = a \cosh x/a - a = a\,(\cosh x/a - 1)$$

Expanding, we obtain

$$z = a\,(1 + (x/a)^2/2! + (x/a)^4/4! + \dots)$$
$$= (x^2/2a)\,[1 + (x/a)^2/12 + (x/a)^4/360 + \dots]$$

which, if the second and succeeding terms are neglected, becomes

$$z = x^2/2a, \text{ or } x^2 = 2az,$$

which is the equation to a parabola.

† For example, if, in a catenary, the sag is 1 per cent of the span, the sag of a corresponding parabola will be $\frac{1}{75}$ of 1 per cent smaller than that of the catenary.

1 per cent of the span, and in these circumstances the wire may be considered to hang in the form of a parabola, in which case the sag will be proportional to the square of the span.

Thus, if w is the weight (in lb.) of unit length of the wire and T is the tension (in lb.), then, by taking moments about one of the supports (s, Fig. 419), we have

$$T\delta = wl \times \tfrac{1}{2}l,$$

whence $$T = wl^2/2\delta$$

and $$\delta = wl^2/2T \quad . \quad . \quad . \quad . \quad . \quad . \quad (44)$$

The tension T is not uniform throughout the span, but increases slightly towards the supports. With small sags, however, the variation is practically negligible.

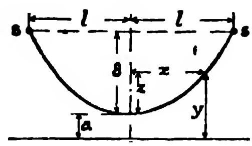


FIG. 419.

In this country, trolley wire is usually erected with a sag of 9 in. in a span of 120 ft., at a temperature of about 65° F. Hence, applying Equation (44) to these conditions, we have $l^2/2\delta = 60^2/(2 \times 0{\cdot}75) = 2400$ so that $T = 2400w$. The following values give the weight per foot of copper trolley wire—

Size of wire (S.W.G.)	00	000	0000
Weight per foot (lb.)	0·367	0·419	0·484

Whence the tensions and stresses in these wires when erected (120 ft. span, 9 in. sag) are—

Size of wire (S.W.G.)	00	000	0000
Diameter of wire (in.)	0·318	0·372	0·4
Area of cross-section (sq. in.) . .	0·095	0·1087	0·1257
Tension in lb. (9-in. sag, 120-ft. span)	880	1005	1160
Stress (lb. per sq. in.)	9270	9240	9230

Effect of temperature on sag and tension. A change in temperature produces changes in the sag and tension, but in calculating the sag at different temperatures the elasticity of the wire must be taken into account. For example, a decrease in temperature tends to reduce the sag, but the increased tension, due to the reduced sag, produces a stretching of the wire, so that the resulting change in the sag is smaller than that calculated by ignoring the elasticity of the material. Thus, consider a wire suspended between two horizontal supports, and let

$2l$ = distance between supports
L_0 = unstretched length of the wire at a temperature $\theta°$ F.
L'_0 = unstretched length of the wire at a temperature $\theta_1°$ F.
L = length of the wire at a temperature $\theta°$ F., when erected with a sag δ and a tension T
L_1 = length of the wire at a temperature $\theta_1°$ F., the corresponding values of the sag and tension being δ_1, T_1
α = coefficient of linear expansion of the material
E = Young's modulus of elasticity of the material
a = area of cross-section of the wire
w = weight of unit length of the wire.

Then, at a temperature $\theta°$, the extension due to the elasticity of the wire is $L - L_0$, and the strain is $(L - L_0)/L_0$. The stress in the wire is T/a; and, as Young's modulus of elasticity = stress/strain, we have $E = (T/a)/[(L - L_0)/L_0]$, from which the unstretched length is obtained as

$$L_0 = L(1 + T/aE)^{-1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

or approximately $L_0 = L(1 - T/aE)$ . . . . . . (45a)

The length (L) corresponding to a sag of δ in a span $2l$ is given with sufficient accuracy by

$$L = 2l[1 + \tfrac{2}{3}(\delta/l)^2]^* \quad . \quad . \quad . \quad . \quad . \quad (46)$$

Substituting in equation (45), we obtain

$$L_0 = 2l[1 + \tfrac{2}{3}(\delta/l)^2]\,(1 + T/aE)^{-1} \quad . \quad . \quad . \quad (45b)$$

Now, if the temperature increases to θ_1, the unstretched length becomes $L'_0 = L_0(1 + a(\theta_1 - \theta))$, and when the wire is erected this length will be stretched to L_1, the corresponding values of the sag and tension being δ_1 and T_1 respectively.

From equations (45, 46) we have

$$L_1 = L_0'(1 + T_1/aE)$$
$$= L_0[1 + a(\theta_1 - \theta)]\,(1 + T_1/aE)$$

and
$$L_1 = 2l[1 + \tfrac{2}{3}(\delta_1/l)^2]$$

Combining these equations with equation (45b) we obtain

$$2l\left\{1 + \frac{2}{3}\left(\frac{\delta}{l}\right)^2\right\}\left(1 + \frac{T}{aE}\right)^{-1} = 2l\left\{1 + \frac{2}{3}\left(\frac{\delta_1}{l}\right)^2\right\}\left(1 + \frac{T_1}{aE}\right)^{-1}\left(\frac{1}{1 + a(\theta_1 - \theta)}\right)$$

Substituting for δ and δ_1, we have

$$\left\{1 + \frac{1}{6}\left(\frac{wl}{T}\right)^2\right\}\left(1 + \frac{T_1}{aE}\right)(1 + a(\theta_1 - \theta)) = \left\{1 + \frac{1}{6}\left(\frac{wl}{T_1}\right)^2\right\}\left(1 + \frac{T}{aE}\right)$$

which, when simplified by neglecting the product of small quantities (such as $a(\theta_1 - \theta)\,(wl/T)^2$, $\tfrac{1}{6}T_1(wl/T)^2/aE$, etc.), reduces to

$$a(\theta_1 - \theta) + \tfrac{1}{6}(wl/T)^2 - \tfrac{1}{6}(wl/T_1)^2 + (T_1 - T)/aE = 0$$

or
$$a(\theta_1 - \theta) = \tfrac{1}{6}(wl)^2(1/T_1^2 - 1/T^2) + (T - T_1)/aE \quad . \quad . \quad (47)$$

From this equation we can easily calculate the change of temperature required to produce a given change in the tension. If, however, we require the tension T_1 corresponding to the temperature θ_1, the solution

* The length of any curve of which the equation is known is given by

$$L = \int\sqrt{[1 + (dy/dx)^2]}dx$$

Applying this to the catenary $y = a\cosh x/a$, we obtain $L = a\sinh x/a$.

Expanding, we have

$$L = a[x/a + (x/a)^3/3! + (x/a)^5/5! + \ . \ . \ .]$$
$$= x[1 + \tfrac{1}{6}(x/a)^2]$$

if the third and succeeding terms are neglected.

In the case of a suspended wire, for which the span is $2l$, we have $x = 0$ at mid-span and $x = l$ at end of span. Hence, the length of wire in one-half of the span is given by

$$L = l[1 + \tfrac{1}{6}(wl/T)^2] = l[1 + \tfrac{2}{3}(\delta/l)^2]$$

is not quite so easy, as it involves a cubic equation. Thus, expanding and re-arranging terms, we obtain

$$T_1^3 + T_1^2 aE[a(\theta_1 - \theta) + \tfrac{1}{6}(wl/T)^2 - T/aE] = \tfrac{1}{6}aEw^2l^2$$

which may be written—

$$T_1^2[T_1 + aE[a(\theta_1 - \theta) + \tfrac{1}{6}(wl/T)^2 - T/aE] = \tfrac{1}{6}aEw^2l^2$$

whence $$T_1 = \sqrt{\frac{0{\cdot}166aE(wl)^2}{T_1 + aE[a(\theta_1 - \theta) + \frac{1}{6}(wl/T)^2] - T}} \quad . \quad . \quad . \quad (48)$$

or $$T_1 = \sqrt{A/[T_1 - (T - B)]}$$

where $A = 0{\cdot}166aE(wl)^2$ and $B = aE[a(\theta_1 - \theta) + \frac{1}{6}(wl/T)^2]$

This equation may be solved by assuming an appropriate value for T_1 and calculating the value of the radical, which should agree with the assumed value if the latter has been correctly chosen. A slide-rule greatly facilitates this method of solution.

Example. Determine the tension in a 120-ft. span of copper trolley wire at temperatures of 40° F. and 100° F. having given that the trolley wire has been erected with a sag of 9 in. at a temperature of 65° F.

In this case

$a = 0{\cdot}1257$ sq. in., $w = 0{\cdot}484$ lb., $E = 18 \times 10^6$ lb. per sq. in.

$a = 0{\cdot}0000093$, and from the example on p. 579, $T = 1160$ lb.

Hence, substituting these values in equation (48), we obtain

$$T_1 = 1000\sqrt{\{319/[T_1 + 21(\theta_1 - 65) + 236 - 1160]\}}.$$

For a temperature of 40° F. we have

$$T_1 = 1000\sqrt{[319/(T_1 - 1450)]} = 1578 \text{ lb.}$$

At 100° F. the equation for the tension becomes

$$T_1' = 1000\sqrt{[319/(T_1' - 187)]}$$

which gives $T_1' = 752$ lb.

The sags corresponding to these tensions are obtained from equation (44). Thus, at 40° F., $\delta_1 = 0{\cdot}484 \times 60^2/(2 \times 1578) = 0{\cdot}552$ ft., or 6·63 in.; and at 100° F., $\delta_1' = 0{\cdot}484 \times 60^2/(2 \times 752) = 1{\cdot}16$ ft., or 13·9 in.

Summarizing the results, we have

Temperature (degrees F.)	40	65	100
Sag (in.) . . .	6·63	9	13·9
Tension (lb.) . .	1578	1160	752
Stress (lb. per sq. in.) .	12,550	9230	6000

The **sag to be given to a trolley wire** at any temperature should be such that, under the severest conditions of weather, the wire is not stretched beyond its elastic limit. In tramway practice these conditions are represented by a temperature of 22° F., and a horizontal wind pressure of 20 lb. per sq. ft. If D is the diameter of the trolley wire in inches, the wind pressure will produce a loading of $0{\cdot}6D \times 20/12 = D$ lb.* per foot run of the wire, and this must be added vectorially to the weight per foot run in order to obtain the resultant load. Thus, if w (lb.) is the weight per foot of the wire, the resultant load per foot will be $w' = \sqrt{(w^2 + D^2)}$, and the tension T' is given by

$$T' = \sqrt{(l^2/2\delta')}\sqrt{(w^2 + D^2)} \quad . \quad . \quad . \quad . \quad (49)$$

where δ' is the sag corresponding to these conditions. This sag is, of

* The total wind pressure on a cylindrical body = 0·6 × pressure on a flat surface of the same area as the projected area of the cylinder.

course, to be measured in the plane of the wire, which will make an angle of $\tan^{-1} D/w$ to the vertical.

Applying these conditions to the above example, we obtain

$$w' = \sqrt{(0{\cdot}484^2 + 0{\cdot}4^2)} = 0{\cdot}628 \text{ lb.}$$

and from Equation (48),

$$T' = 1000\sqrt{[535/(T' - 1674)]} = 1830 \text{ lb.}$$

which is within the elastic limit.

Tension in span wires. The sag in a span wire depends on (1) weight supported; (2) width of road; (3) permissible tension.

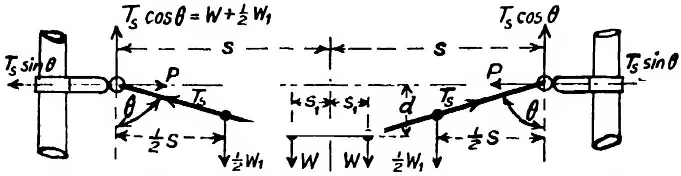


FIG. 420.—Diagram representing General Conditions of Loading of Span Wire.

In the general case of span-wire construction the conditions of loading are as represented in Fig. 420, in which

W = weight of each trolley wire and supporting device per span
W_1 = weight of the span wire
T_s = tension in the span wire
θ = inclination of the span wire to the vertical
$2s$ = horizontal distance between supports of span wire
$2s_1$ = distance apart of trolley wires
d = sag of span wire.

By taking moments about the centre of the span we have

$$T_s \sin\theta \times d - T_s \cos\theta \times s - \tfrac{1}{2}W_1 \times \tfrac{1}{2}s - Ws_1$$
$$= \{\tfrac{1}{2}(2W + W_1)s - \tfrac{1}{4}W_1 s - Ws_1\}$$
$$= W(s - s_1) + \tfrac{1}{4}W_1 s$$

Writing $T_s \sin\theta = P$, we have

$$P = [W(s - s_1) + \tfrac{1}{4}W_1 s]/d \quad . \quad . \quad . \quad . \quad (50)$$

Now $T_s \sin\theta$, or P, is the horizontal pull on the pole, hence

$$T_s = P/\sin\theta = P\sqrt{[d^2 + (s - s_1)^2]}/(s - s_1) = P\sqrt{[1 + d^2/(s - s_1)^2]}$$
$$= P[1 + d^2/2(s - s_1)^2]$$

The **weights of some typical overhead fittings** are given below—

Straight-line hanger with bolt	3 lb.
Double pull-off with bolt	$4\frac{3}{4}$,,
Single pull-off with bolt	$1\frac{1}{4}$,,
12-in. ear	$1\frac{1}{2}$,,
6-in. ear	$\frac{3}{4}$,,
Globe strain insulator ($2\frac{1}{2}$ in. dia.)	1 ,,
Prescot loop type porcelain insulator ($4\frac{3}{8}$ in.)	1 ,,
Section insulator	18 ,,
Two-way switching frog	15 ,,
Two-way trailing frog	14 ,,
Crossing	18 ,,

Examples. (1) Determine the tension in a 7/·125″ span wire when supporting two 0·4-in. trolley wires 8 ft. apart, the sag in the span wire being 1 ft. The poles of each span are spaced at 43 ft. apart, with a distance of 120 ft. between spans, and the span wire is attached to bracket arms 18 in. long. We have

Weight of 120 ft. 0·4-in. trolley wire = 0·484 × 120	= 58 lb.
Weight of hanger, ear, etc..	= 4 ,,
	62 lb.

Weight of 40 ft. 7/·125″ span wire = 0·21 × 40 = 8·4 lb.

The loading is shown in Fig. 421, and from equation (50) we obtain

$$P = 62(20 - 4) + \tfrac{1}{4} \times 8{\cdot}4 \times 20 = 1034 \text{ lb.}$$

and

$$T_s = 1034[1 + 1/(2 \times 16^2)] = 1036 \text{ lb.}$$

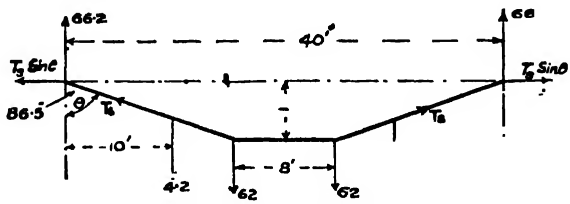


FIG. 421.—Loading of Span Wire in Example (1).

(2) Similar conditions to above, but section insulators fitted to the trolley wires. We have

Weight of 120 ft. 0·4-in. trolley wire	= 58 lb.
Weight of section insulator with strain insulators . .	= 20 ,,
	78 lb.

Assuming that the 7/·125″ span wire is used, we obtain,

$$P = 1283 \text{ lb., and } T_s = 1285{\cdot}5 \text{ lb.}$$

If the trolley wires are anchored in the manner shown in Fig. 418, the span wire supporting the section insulators will be relieved of a portion of the load. A reference to p. 578 will show that the "medium" pole will be suitable for these cases.

Calculation of tension in pull-off wires. Consider a curve on a tramway system where a single trolley wire is supported from span wires arranged radially as in Fig. 422. The points of attachment of the pull-offs to the trolley wire are arranged on an arc of a circle of radius R ft. The trolley wire, in virtue of its tension, will form a series of chords in this circle. If T is the tension in the trolley wire, the horizontal component of this in the direction of the span wire will be $2T \cos \alpha$. As the triangles ABD and AOE are similar, we have

$$\cos \alpha = AD/AB = AE/AO = \tfrac{1}{2}l_1/R$$

In addition to this tension, the span wire is loaded with a tension due to the weight of the pull-off, trolley wire, etc. This additional tension can be calculated by a method similar to that adopted with span wire construction. If P_1' represents the horizontal force due to the weight

of the trolley wire and fittings, the pull on the poles to which the span wire is attached will be

$$P_1 = P_1' + Tl_1/R \qquad (51)$$

on the outside of the curve, and

$$P_2 = P_1' - Tl_1/R \quad . \quad . \quad . \quad . \quad . \quad . \qquad (51a)$$

on the inside of the curve.

The tensions in each portion of the span wire will be $P_1/\sin\theta_1$ and $P_2/\sin\theta_2$, where θ_1, θ_2 are the inclinations of the span wire to the vertical.

When Tl_1/R is greater than P_1', the portion of the span wire on the inside of the curve is not required. In this case it is usual to arrange the pull-off wires as in Fig. 412, and the problem does not permit of

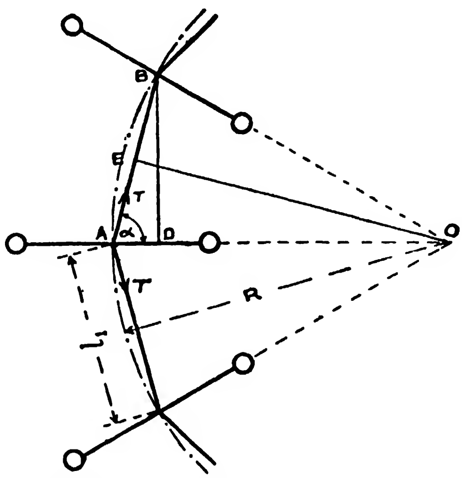


FIG. 422.—Diagram showing Position of Trolley Wire on Curve.

such an easy solution as above, due to an incomplete knowledge of the tension in the trolley wire, which in practice is adjusted to some arbitrary value when the line is erected. The method of calculation is better elucidated by working through an example.

Example. Determine the tensions in the pull-off wires and the sizes of poles for a single 0·4-in. trolley wire on a right-angle curve, of which a layout showing the positions available for the poles, is given in Fig. 423. There are seven pull-offs, which are attached to the trolley wire at a radius of 50 ft. The tension in the trolley wire on the curve may be assumed at 700 lb. At each end of the curve there is a straight line which is suitably anchored, the tension in the anchor wire being assumed at 400 lb. The length of the first span of the straight sections is 60 ft.

The tension in the wires attached to pull-offs Nos. 3, 4, 5 can be obtained from a slight modification of equation (51). Thus, if ϕ is the angle between the pull-off wire and a radius vector produced (Fig. 423), the horizontal pull on the pole is given by

$$P_1 = P_1' + Tl_1/R \cos\phi$$

where the first term is the pull due to the weight of trolley wire, fittings,

etc., attached to the pull-off, and the second term is the component of the trolley-wire tension in the direction of the pull-off wire. To obtain P_1', let

W = weight of trolley wire, ear, and pull-off
W_2 = weight of pull-off wire
s = length of pull-off wire
d = sag in pull-off wire.

Then $$P_1' = (Ws + \tfrac{1}{2}W_2 s)/d$$

If we assume that 7/·125" steel wire is used for all the pull-off and span wires, then the weight of this wire for No. 4 pull-off will be $44 \times 0{\cdot}21 = 9{\cdot}2$ lb.*

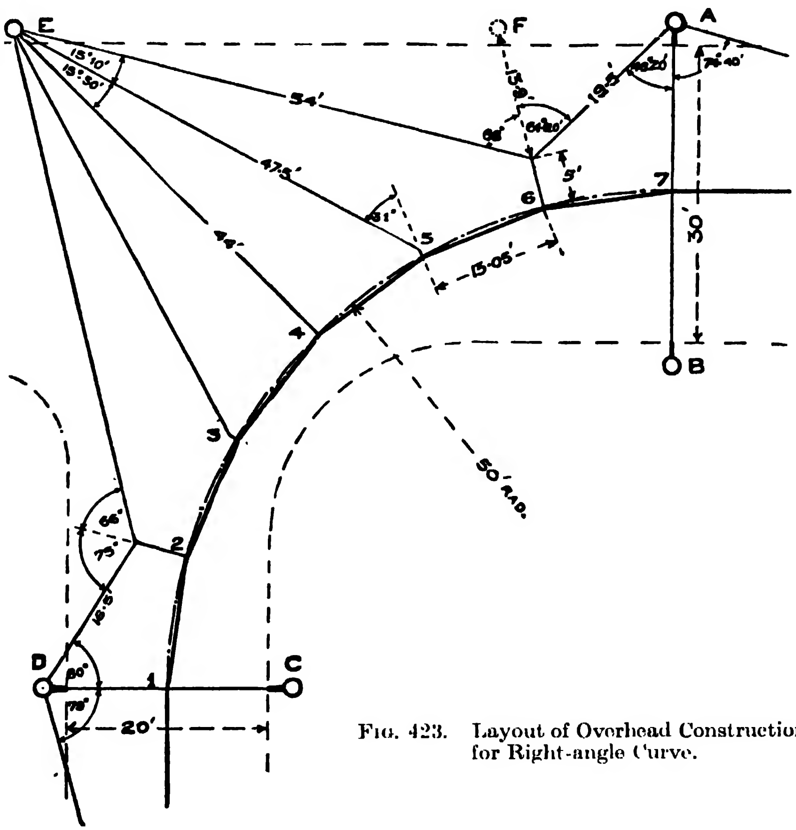


Fig. 423. Layout of Overhead Construction for Right-angle Curve.

and $47{\cdot}5 \times 0{\cdot}21 = 10$ lb. for pull-offs Nos. 3 and 5. The distance between the pull-offs being 13·05 ft., we have: weight of trolley wire, ear, and pull-off $= 13{\cdot}05 \times 0{\cdot}484 + 1 + 3{\cdot}5 = 10{\cdot}8$ lb. If the sag in the pull-off wires is 4 ft., we obtain $P_1' = \frac{1}{4}(10{\cdot}8 \times 44 + 9{\cdot}2 \times 22) = 169$ lb. for No. 4, and 188 lb. for Nos. 3 and 5.

Hence, the tension in pull-off wire No. 4, which is radial, will be

$$169 + 700 \times 13{\cdot}05/50 = 169 + 183 = 352 \text{ lb.},$$

and the tension in Nos. 3 and 5 will be

$$188 + 183/\cos 31° = 188 + 213 = 401 \text{ lb.}$$

* The effect of the inclination of the pull-off wires is neglected in the calculations of weight and tension.

We have now to deal with the bridles at Nos. 2 and 6, which can be done in the following manner. Consider the bridle at No. 6 replaced by a radial pull-off wire attached to a pole at F; calculate the tension in this wire, and resolve this tension into components along the directions of the bridle.* In this manner we obtain 266 lb. for the tension in the radial pull-off wire, and $266/(\cos 66^\circ + \cos 61{\cdot}3^\circ) = 300$ lb. in the bridle wire. Treating the bridle at No. 2 in a similar manner, we obtain the tension in the bridle wire as 360 lb.

The span wires Nos. 1 and 7 now demand attention. If we assume the sag in the span wire as 1 ft., we obtain, from equation (50), values of 128 lb. and 201 lb. for the tension in No. 1 and No. 7 respectively.

The resultant pull on pole E will be in the direction of pull-off wire No. 4, and its magnitude will be

$$352 + 2 \times 401 \cos 15{\cdot}83^\circ + (300 + 360) \cos 31^\circ = 1690 \text{ lb.}$$

The resultant pull on pole A is 540 lb., at an angle of 18° with the span wire (straight-line side), while the resultant pull on pole D is 393 lb. at an angle of 12° with the span wire (straight-line side).

Summarizing, we have the following values for the pull on the poles: A, 540 lb.; B, 201 lb.; C, 128 lb.; D, 393 lb.; E, 1690 lb.; while the tensions in the respective span and pull-off wires are: No. 1, 128 lb.; No. 2, (bridle), 360 lb.; No. 3, 401 lb.; No. 4, 352 lb.; No. 5, 401 lb.; No. 6 (bridle), 300 lb.; No. 7, 201 lb.; anchor wires, 400 lb.

Pole E must therefore be of the "heavy" class, while for the poles A, B, C, D the "light" class could be used.

The calculations for a double track are performed in a similar manner, but in this case the tension in the outer pull-off wires will be $P_1' + Tl_1/R \cos \phi$, and the tension in the wire between the trolley wires will be Tl_1/R.

If, with the assumed value for the tension in the trolley wire, the pull on the poles is excessive, then a lower value must be adopted and care taken that this value is not exceeded when the line is erected.

* As the bridle wire is threaded through a ring at the end of the pull-off wire, the tension in each portion of it will be the same.

CHAPTER XXV

OVERHEAD CONSTRUCTION ON RAILWAYS

Part I. General Considerations

Overhead construction is usually desirable for operating pressures of 1500 volts and above.

A bow collector is generally used instead of a trolley wheel, since, with the former, no frogs or crossings are required at junctions. Moreover, this type of collector is suitable for much higher speeds and larger currents than the trolley wheel, while the chances of it leaving the trolley wire are very remote. The bow collector, however, due to its greater inertia, requires a level trolley wire in order that contact may be maintained between the bow and wire at high speeds.

The trolley wire must, therefore, be suspended with a very small sag, and to obtain this result without excessive tension in the wire, the span must be relatively short, i.e. of the order of 10 ft. to 15 ft. For such short spans an indirect method of suspension is desirable; the trolley wire being supported by another wire, which is suspended with considerable sag between supports fixed at moderate distances apart. The wire from which the trolley wire is supported is called the "catenary" or "messenger," and if this wire is insulated from the supports, no insulated hangers are necessary for the trolley wire. The object of the large sag in the catenary wire is to maintain the position of the trolley wire practically constant for the range of temperature occurring in practice.

Catenary construction. Present-day catenary construction on railways is of either the single catenary or the compound catenary. The former consists of a suspended steel wire A, Fig. 424(a), from which the trolley wire C is supported by means of droppers B, clipped to A and C at equidistant horizontal intervals. On straight (or tangent) track the span of the catenary wire may be from 150 ft. to 300 ft., with sags of from 3 ft. to 6 ft. respectively, and the distance apart of the droppers varies from 10 ft. to 15 ft. On curves the span is reduced and the trolley wire is maintained in position by pull-off wires.

The Siemens-Schuckert compound catenary consists of three wires, all in the same vertical plane. The upper wire A, Fig. 424(b), is the catenary wire, and is insulated from the supporting structures. From this wire the intermediate wire B is supported by droppers, D, clipped to both wires, and the trolley wire C is supported from the intermediate wire by the loops E. The trolley wire is maintained under a definite and constant tension by means of automatic tightening gear, and the loops E allow longitudinal movement of the trolley wire to take place without straining the suspension wires.

The **catenary wire** is usually of stranded steel, of seven or more strands, having the following average properties—

Ultimate tensile strength . . .	90 tons per sq. in.
Elastic limit	40 tons per sq. in.
Modulus of elasticity	30×10^6 lb. per sq. in.
Coefficient of linear expansion (per 1° F.) .	0·0000064

Calculation of tension in catenary wire. The sag of the catenary wire generally does not exceed 3 per cent of the span, and if the wire were loaded only with its own weight, the tension could be calculated in the same manner as for a tramway trolley wire, as the curve of the sag

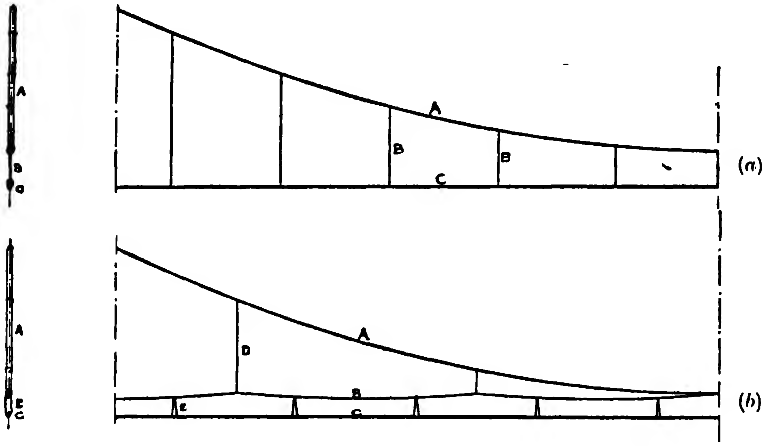


FIG. 424.—Types of Catenary Construction.
(*a*) single catenary ; (*b*) compound catenary.

could be considered to be a parabola.* The effect of the trolley wire is equivalent to a series of equal weights hung from the catenary wire at equi-distant horizontal intervals. If the weight of the catenary wire

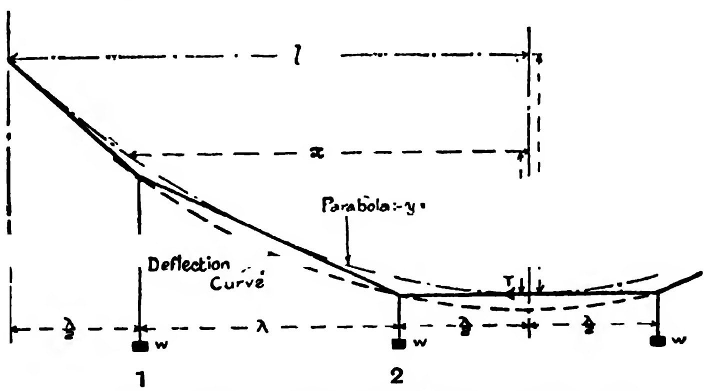


FIG. 425.—Loading of Catenary Wire due to Trolley Wire.

is neglected, the sections between the droppers are straight lines, and form the envelope to the parabola $y = x^2/2(T/W)\lambda$, where y is the ordinate corresponding to a distance x from the centre of the span, T the horizontal tension at the mid-span, and λ the distance apart of the weights W (Fig. 425).

* With a sag of 3 per cent of the span the error in calculating the sag from the parabola equation (instead of the catenary) is 0·2 per cent, while with a 2 per cent sag the error is 0·05 per cent.

The curve* joining the points of attachment of the droppers to the catenary wire differs slightly from this parabola,† as each section of the catenary wire is tangential to the latter.

In practice, the weight of the catenary wire is comparable with that of the trolley wire, so that the deflection curve will be intermediate between the above curve and the parabola $y = x^2/2T/w'$ (w' being the average weight of the trolley wire, catenary wire, and droppers per foot of horizontal span). The sections of the catenary wire now hang in a series of catenary curves, for which we have no particular interest.

The tension T is determined by considering one-half of the span and taking moments of all forces about the point of support (A, Fig. 425). Since the sag is small in comparison with the span, the weight of the catenary wire per horizontal foot of span may be considered to be identical with the weight per foot of wire. Hence w' may be considered as equivalent to the average weight of the whole suspension per foot run.

Considering an *even* number of droppers per span and taking moments about A (Fig. 425), we have—

$$\begin{aligned} T\delta &= \tfrac{1}{2}\lambda(w\lambda + w_1\lambda + w_2) + \tfrac{3}{2}\lambda(w\lambda + w_1\lambda + w_2) + \tfrac{5}{2}\lambda(w\lambda + w_1\lambda + w_2) + \dots \\ &= [\lambda(w + w_1) + w_2]\lambda\tfrac{1}{2}(1 + 3 + 5 + \dots + (2n - 1)) \\ &= [\lambda(w + w_1) + w_2]\lambda\tfrac{1}{2}n^2\ddagger \\ &= \tfrac{1}{2}l^2(w + w_1 + w_2/\lambda) \\ &= \tfrac{1}{2}w'l^2 \qquad \qquad (52) \end{aligned}$$

where w, w_1, denote the weight per foot of trolley wire and catenary wire respectively; w_2 denotes the average weight of a dropper and clips; $2l$ the distance (in feet) between supporting structures; δ the sag (in feet) of catenary wire at mid-span; λ the horizontal spacing (in feet) of the droppers; n the number of droppers per half-span, the centre one, if any, not being included.

For an *odd* number of droppers per span, we have

$$\begin{aligned} T\delta &= \tfrac{1}{2}(w + w_1)l^2 + w_2\lambda\tfrac{1}{2}(1 + 3 + 5 + \dots + (2n + 1)) \\ &= \tfrac{1}{2}(w + w_1)l^2 + \tfrac{1}{2}w_2\lambda(n + 1)^2\,\| \\ &= \tfrac{1}{2}l^2(w + w_1) + \tfrac{1}{2}w_2\lambda(l^2/\lambda^2 + l/\lambda + \tfrac{1}{4}) \\ &= \tfrac{1}{2}l^2(w + w_1 + w_2/\lambda) + \tfrac{1}{2}w_2\lambda(l/\lambda + \tfrac{1}{4}) \\ &= \tfrac{1}{2}w'l^2 + \tfrac{1}{2}w_2\lambda(n + \tfrac{3}{4}) \qquad \qquad (52a) \end{aligned}$$

Calculation of lengths of droppers. The deflection at any dropper can be obtained by taking moments, about the point of the catenary wire at which the dropper is attached, and dividing by the tension T. Thus for dropper No. 1 (Fig. 425) we have (assuming an *even* number of droppers per span)

$$Ty_1 = \tfrac{1}{2}(w + w_1)(l - \tfrac{1}{2}\lambda)^2 + w_2\lambda(1 + 2 + 3 + \dots + (n - 1))$$

and for dropper No. 2,

$$Ty_2 = \tfrac{1}{2}(w + w_1)(l - \tfrac{3}{2}\lambda)^2 + w_2\lambda(1 + 2 + 3 + \dots + (n - 2))$$

* Called hereafter the "deflection" curve.

† It can be shown that each point on the deflection curve is $(W/T)(\lambda/8)$ vertically below the corresponding point on the above parabola.

‡ The number of terms in the series $1 + 3 + 5 + \dots + (2n - 1)$ is n; hence the sum $= \tfrac{1}{2}n(1 + (2n - 1)) = n^2$. [NOTE $n = l/\lambda$.]

‖ The number of terms in the series $1 + 3 + 5 + \dots + (2n + 1)$ is $n + 1$; hence the sum $= \tfrac{1}{2}(n + 1)[1 + (2n + 1)] = (n + 1)^2$. [NOTE $n = l/\lambda - \tfrac{1}{2}$.]

or generally,

$$Ty_m = \tfrac{1}{2}(w + w_1)\,[l - \tfrac{1}{2}\lambda(2m-1)]^2 + w_2\lambda\tfrac{1}{2}[(n-(m-1))\,(n-m)]^* \qquad (53)$$

where m is the number assigned to the dropper, the one nearest to the support (A, Fig. 425) being No. 1.

Calling these moments M_1, M_2, . . . M_m, we have

$$Ty_1 = M_1,\ Ty_2 = M_2,\ Ty_m = M_m$$

whence $\quad y_1 = M_1/T,\ y_2 = M_2/T, \ldots y_m = M_m/T$ . . . (54)

The lengths of the droppers will be $(y_1 + z)$, $(y_2 + z)$, etc., where z is the distance between the catenary wire and the trolley wire at mid-span.

In cases where approximate results are sufficient, the deflection at each dropper can be obtained by assuming that the deflection curve is the parabola $y = x^2/2T/w'$, y being the deflection at a distance x from mid-span.

Example. Calculation of the deflections and lengths of droppers for an eleven-point single catenary suspension having the following constants—

Length of span ($2l$)	150 ft.
Sag at mid-span (δ)	2·5 ft. (30 in.)
Distance between catenary wire and trolley wire at mid-span (z)	0·66 ft. (8 in.)
Numbers of droppers per span . . .	11
Spacing of droppers (λ)	13·63 ft.
Size of trolley wire	0·46 in. dia. (= 1/0 B. & S.G.)
Weight per foot of trolley wire (w) . .	0·641 lb.
Size of catenary wire	7/16 in. dia.
Weight per foot of catenary wire (w_1) . .	0·384 lb.
Average weight of dropper and clips (w_2) .	0·5 lb.

The average weight (w') of trolley wire, catenary wire, dropper, and clips per foot run

$$= 0{\cdot}641 + 0{\cdot}384 + 0{\cdot}5/13{\cdot}63 = 1{\cdot}062 \text{ lb.}$$

Since there are 11 droppers per span, the value of n in equations (52, 53) will be 5. Hence the tension in the catenary wire at mid-span—obtained from equation (52a)—is

$$T = (\tfrac{1}{2} \times 1{\cdot}062 \times 75^2 + \tfrac{1}{2} \times 0{\cdot}5 \times 13{\cdot}63 \times 5{\cdot}75)/2{\cdot}5 = 1214 \text{ lb.}$$

From equation (53a) values for M_1, M_2, etc., are obtained as follows—

$$\begin{aligned} M_1 &= \tfrac{1}{2}(0{\cdot}641 + 0{\cdot}384)\{75 - \tfrac{1}{2} \times 13{\cdot}63\ (2 \times 1 - 1)\}^2 \\ &\quad + \tfrac{1}{2} \times 0{\cdot}5 \times 13{\cdot}63\ \{(5-(1-1))\ (5-(1-2))\} \\ &= 2482 \\ M_2 &= 1593 \\ M_3 &= 897{\cdot}4 \\ M_4 &= 402{\cdot}5 \\ M_5 &= 102 \end{aligned}$$

The deflections are obtained by dividing these values by the tension (1214 lb.), and the lengths of the droppers will be 8 in. greater than the deflections.

A summary of the results obtained by this method and by the approximate method is given in Table XXI.

* The series for the mth dropper is $1 + 2 + 3 + \ldots + (n-m)$, the number of terms being $(n-m)$. The sum of this series is $\tfrac{1}{2}(n-m)(1+(n-m))$, or $\tfrac{1}{2}(n-(m-1))(n-m)$. For an odd number of droppers per span, the sum of the series becomes $\tfrac{1}{2}(n-(m-1))(n-(m-2))$, and Equation (53) takes the form

$$Ty_m = \tfrac{1}{2}(w + w_1)\,\{l - \tfrac{1}{2}\lambda\,(2m-1)\}^2 + \tfrac{1}{2}w_2\lambda(n-(m-1))\,(n-(m-2))\} \qquad (53a)$$

In applying the approximate method—i.e. assuming the deflection curve to be a parabola—we have

$$T = w'l^2/2\delta = 1195 \text{ lb., and } y = x^2/(2 \times 1195/1{\cdot}062) = x^2/2250$$

as the equation to the deflection curve.

TABLE XXI

Dropper No. .			3							10	
Distance from mid-span (ft.)	68·2	54·5	40·9	27·26	13·63	0	13·63	27·26	40·9	54·5	68·2
Deflection—by method of moments (ft.) .	2·043	1·312	0·74	0·332	0·084	0	0·081	0·332	0·74	1·312	2·043
Deflection—by approximate method (ft.) .	2·063	1·323	0·743	0·33	0·0826	0	0·0826	0·33	0·743	1·323	2·063
Length of dropper (in.)	32·5	23·8	16·9	12	9·01	8	9·01	12	16·9	23·8	32·5
Approximate length of dropper (in.) . . .	32·8	23·9	16·9	11·96	9	8		11·96	16·9	23·9	32·8

Effect of temperature on level of trolley wire. The level of the trolley wire will be affected to some extent by changes of temperature, the variation of level depending upon the variation of the sag of the catenary wire with temperature. In considering the effects of temperature on the catenary wire, the latter will be treated as a simple catenary.

Thus, if l = length (in feet) of half the span

w' = equivalent weight per foot of catenary wire, trolley wire, and droppers

a = area of cross-section of catenary wire

α = coefficient of linear expansion

E = modulus of elasticity

T, T_1 = tension at lowest point of catenary wire corresponding to temperatures θ, θ_1 respectively

δ, δ_1 = sag at mid-span corresponding to temperatures θ, θ_1, respectively

then $\alpha(\theta_1 - \theta) = \frac{1}{6}(w'l)^2\,(1/T_1^2 - 1/T^2) + (T - T_1)/aE$.

Now $\delta = w'l^2/2T$, and $\delta_1 = w'l^2/2T_1$; therefore, on substituting for T and T_1, we obtain

$$\alpha(\theta_1 - \theta) = \tfrac{2}{3}(\delta_1^2 - \delta^2)/l^2 - (w'l^2/2aE)\,(1/\delta_1 - 1/\delta) \qquad . \qquad . \qquad (56)$$

which gives the relation between the sag and the temperature.

The value of α for steel is 0·0000064 (per 1° F.), and E should be taken not higher than 25×10^6 lb. per sq. in. for stranded steel wires.*

Hence if the catenary wire in the above example is erected with the specified sag at 60° F., the sag at various temperatures, calculated from equation (56), will be –

Temperature (° F.) .	24·3	42	60	78·9	98·1	118·2
Sag (in.)	26	28	30	32	34	36

* This value for E is considerably below that (30×10^6) for hard drawn steel, the low value being due to the tightening up of the strands with the load.

Thus the trolley wire, as a whole, will be level only at one temperature, and at other temperatures the sections between the supporting structures will be above or below their normal position, due to the variation of the sag in the catenary wire. For the case under consideration, if the trolley wire is level at 60° F., then, at the extreme temperatures of 22° F. and 100° F., the portion at the centre of the span will be respectively 4·25 in. above and 4·2 in. below the normal position.

Considering the sections of trolley wire between the droppers, if each dropper were definitely anchored in position, the conditions would be similar to those in tramway work, and the sag in each section, due to its own weight, would depend upon the tension, temperature, etc., as explained in Chapter XXIV.

An approach to these conditions is obtained in the type of construction originally installed on some American railways, where rigid droppers, fixed to the catenary and trolley wires, were adopted.

With this type of construction, if there is any appreciable sag in the sections of the trolley wire between the droppers, the passage of the bow collector will produce waves in the wire, and as the latter is rigidly supported at the droppers, "pounding" or "hammering" will occur at these points. On the other hand, if the trolley wire is flexibly supported by flexible or loop droppers, the latter will accommodate themselves to any waves in the wire. In this connection the following remarks (abstracted from a paper by Mr. W. N. Smith*) are of interest--

"With the plain type of catenary construction, where no take-up devices are employed, the result is that the sections between the hangers (droppers) become slack enough in warm weather to cause the sliding bows to pound kinks into the wires at the hanger points. . . . The only remedy for this situation . . . is to pull the wire sufficiently tight so that its strain at maximum temperature will not be less than 2000 lb. for a 0·46-in. wire. If the minimum tension at 100° F. is to be 2000 lb.; at 0° F. it will be about 5000 lb. and the elastic limit is reached at 5817 lb. It is to be expected that copper trolley wire, pulled tight enough to be effective at maximum temperatures, will be likely to get pulled beyond the elastic limit in the course of a season or two. . . . These considerations may explain much of the trouble that has been experienced with plain catenary construction, using hard-drawn trolley wire. . . .

"This warm-weather slackness can be obviated where a wire can be pulled sufficiently tight to be at a minimum of 2000 lb. at a high temperature . . . which can be done with 'phono-electric,' steel, or copper-clad steel wire.

"It is the writer's belief that without upwardly yielding hangers, it is necessary to maintain a minimum tension of at least 2000 lb.; and the only excuse for maintaining a lower tension is the ability of the trolley wire to yield at the hangers."

Layout of trolley wire. The position of the trolley wire relatively to the track should be such that the contact surface of the bow collector will be worn uniformly throughout its width. To obtain this result, it is necessary to "stagger" the trolley wire with respect to the centre line of the track, a stagger of 9 in. on each side of the centre line being the

* "Electric Railway Catenary Trolley Construction," *Trans. A.I.E.E.*, v. 29, p. 849.

usual allowance,* although the value is influenced by the design of the bow, amount of side sway in the trolley wire, etc.

At curves, the super-elevation of the track rails and the swing or oscillation of the coaches must be carefully considered in locating the position of the trolley wire, since a slight tilt of the coach will correspond to a relatively large transverse movement of the bow on the trolley wire. On sharp curves, precautions have to be taken to see that the position of the track rails, at the time of installation of the overhead construction, is maintained, as any " slewing " or alteration in the super-elevation of the track rails may result in the bow leaving the trolley wire. This will be appreciated by Fig. 426, which represents an end view of a coach

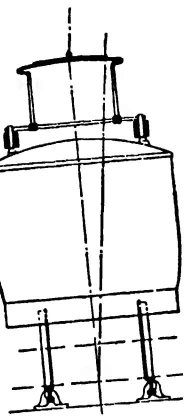


FIG. 426.—Showing Tilt of Coach due to Super-elevation of Track.

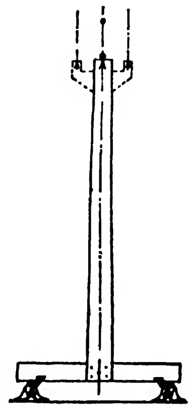


FIG. 427. -T-square for setting Trolley Wire.

with a bow collector on a curve. The correct position of the trolley wire can be obtained when the super-elevation of the track,† height of trolley wire above the track, and particulars of the coaches are known. In practice, it is more convenient to adopt the T-square method, as indicated in Fig. 427. The head of the T-square is arranged to fit the gauge of the track rails, and the centre line of the track is marked on the end of the blade (which may be adjustable vertically). With this device the correct stagger of the trolley wire can be obtained under all conditions.

PART II. EXAMPLES OF OVERHEAD CONSTRUCTION

Direct suspension. This form of construction is suitable for railways

* The zigzag of the trolley wire should be arranged alternately on each side of the centre line of the track. For instance, in the Simplon Tunnel, the trolley wire is staggered in sections of 1 kM, the sections being arranged alternately on the right and the left of the centre line of the track. In this manner, the life of the wearing strips on the bows was trebled, the original staggering being arranged symmetrically throughout. See *The Electrician*, vol. 72, p. 58.

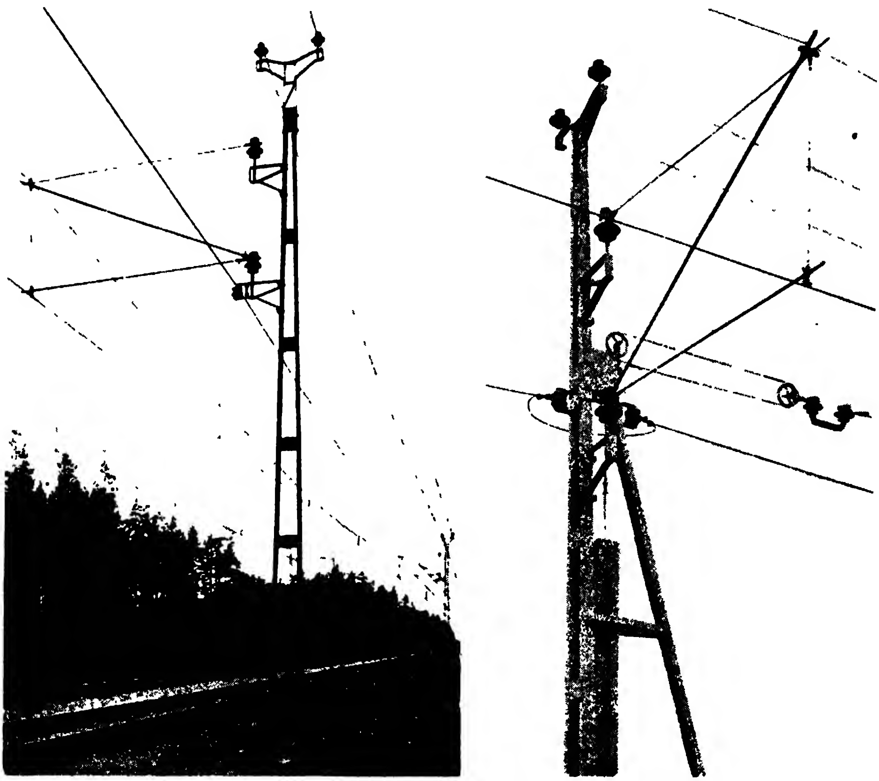
† The super-elevation for standard gauge can be obtained from formula

$$E = 3{\cdot}8\ V^2/R$$

where E = super-elevation in inches, V = velocity of train in ml.p.h., and R = radius of curve in ft.

operating at low speeds. It is employed on many high-voltage, direct-current light railways, and has an extensive application on the three-phase railways of Northern Italy, to which reference is made later.

The method of suspending the trolley wire is similar to that employed with span-wire and bracket-arm tramway overhead construction, but the hangers have porcelain insulation and are arranged for a sliding current



FIGS. 428, 429.– Overhead Construction on Swedish State Railways (A.S.E.A.) FIG. 428, Standard Span on Straight Track; FIG. 429, Detail of Automatic Tightening Device.

collector instead of a trolley wheel. Examples of construction are given later in connection with three-phase railways.

Single catenary construction. This form of construction is suitable for railways on which the traffic is not exceptionally heavy.

Representative views of the construction on the **Swedish and Norwegian State Railways** are shown in Figs. 428–431. The catenary wire is supported by cantilever trusses, each of which is supported by a pair of insulators mounted vertically above each other on a pole at one side of the track. This design was adopted in order that the insulators should not be subjected to the hot blast from steam locomotives which may occasionally run over the track. The lower insulator supports also the

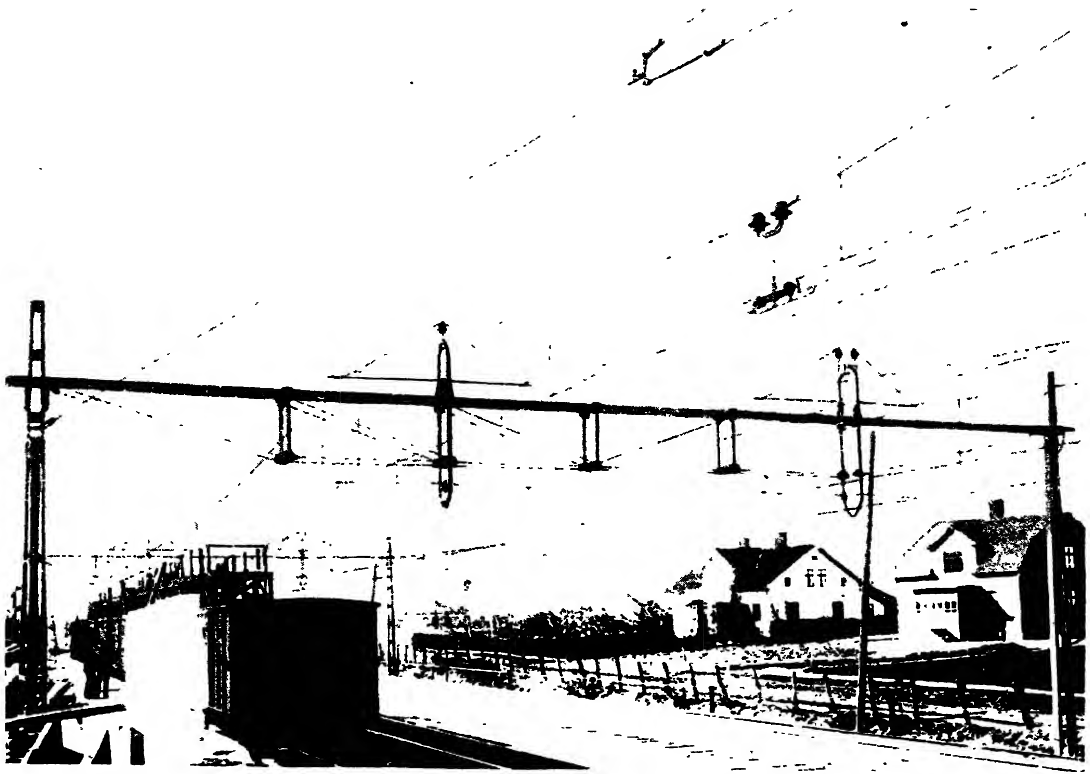


Fig. 430.—Overhead Construction on Swedish State Railways, showing Section Insulator and Equalizing Lever (A.S.E.A.).

pull-off or push-off; and both this member and the tubular compression member of the truss are hinged to the insulator in order not to restrict the vertical flexibility of the trolley wire. Moreover, the pins of both insulators fit loosely into the supporting brackets so as to allow small longitudinal movements of the wires, due to changes of temperature, to take place.

The trolley wire is of hard-drawn copper, having a cross-sectional area of 80 sq. mm. (0·124 sq. in.). The catenary wire is of stranded steel

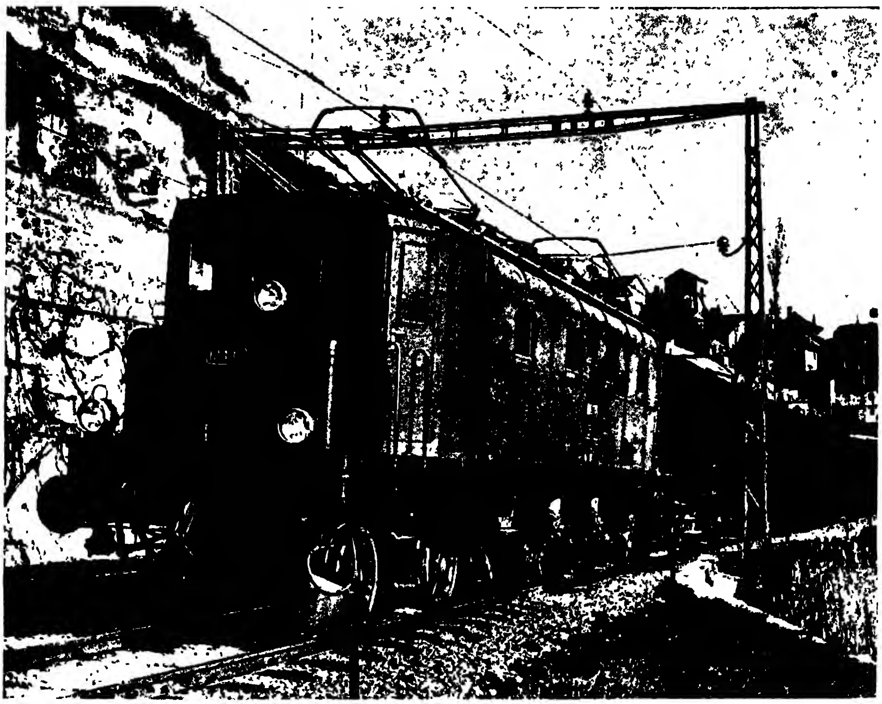


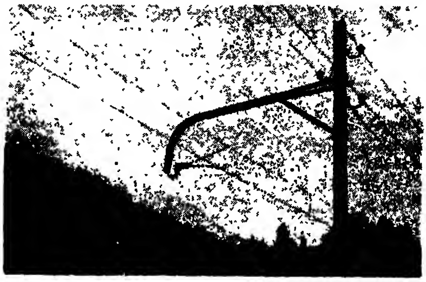
FIG. 431.—Gantry Construction on Swiss Federal Railways (showing also Brown-Boveri Passenger Locomotive).

and has a cross-sectional area of 50 sq. mm. (0·0775 sq. in.). The normal span on straight track is 60 m. (200 ft.), and the droppers are spaced 20 m. (66 ft.) apart. The droppers are of steel wire about 5 mm. (0·2 in.) diameter; the clips are of bronze and are light in weight so as not to produce "hard spots" in the trolley wire.

Both trolley and catenary wires are divided into sections, the normal length of which is 1500 m. (0·93 ml.). Each section is anchored at its mid-point, and both ends are strained by 500 kg. (1100 lb.) weights, Fig. 429, so as to maintain a constant tension in the wires, the tension being applied to the two (trolley and catenary) wires through an equalizing lever, which can be seen in Fig. 430. This feature of maintaining a constant tension in the trolley and catenary wires is applied also to shorter sections at sidings, etc., but when the length of the section

is less than 200 m. (650 ft.), one end is anchored and the other end is strained by springs. By these means, with droppers spaced 20 m. (66 ft.) apart, a sag of about 5 cm. (2 in.) is maintained in the trolley wire over a temperature range of from − 35° C. to + 40° C.

Views of typical single-track and double-track construction on the **Swiss main-line railways** are given in Figs. 431, 432. The catenary wire is supported by pin-type porcelain insulators, which are fixed either to gantries or bracket arms. In some cases a single insulator is employed



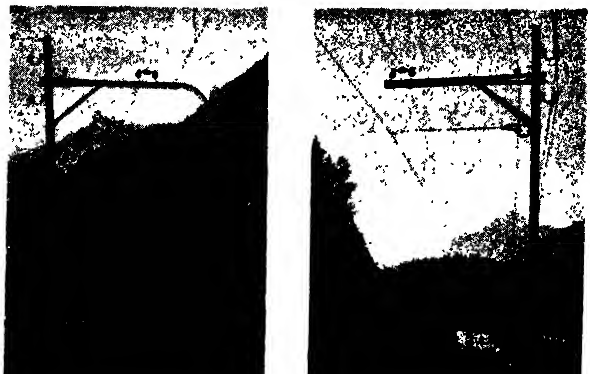


FIG. 432.—Overhead Construction, at Altitude of 4000 ft., on the Bern-Lötschberg-Simplon Railway.

(Fig. 431), but in other cases (e.g. at the higher altitudes) a double set of insulators—consisting of a spool-type insulator fixed to two pin-type insulators (Fig. 432)—is employed.

The trolley wire is maintained in its correct position relatively to the track by light tubular pull-offs, one end of which is clipped to the trolley wire and the other end is hinged to a pin-type insulator fixed to the pole. In those parts of the system where double insulation is employed for the catenary wire, a double insulator is employed for the pull-offs; the end of the pull-off tube being cemented into a spool-type insulator which is hinged to a pin-type insulator fixed to the pole.

The trolley wire is of hard-drawn copper, having a cross-sectional area of 107 sq. mm. (0·166 sq. in.); and the catenary wire is of stranded

steel, having a cross-sectional area of 50 sq. mm. (0·0775 sq. in.). The normal span is 60 m. (200 ft.), but in some cases spans of 100 m. (330 ft.) are adopted. The droppers are spaced 10 m. (33 ft.) apart, and consist of

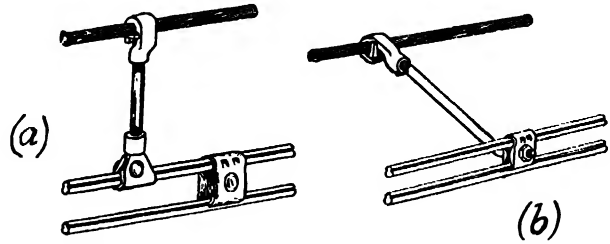


FIG. 433.—Hangers for Straight and Curved Track.

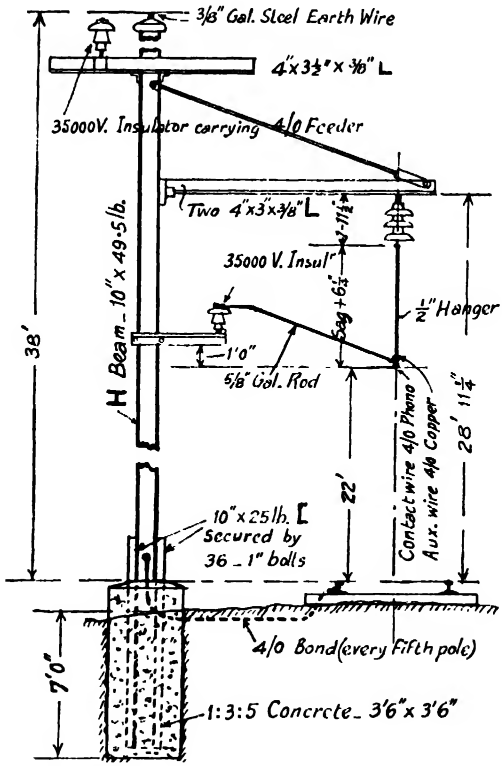


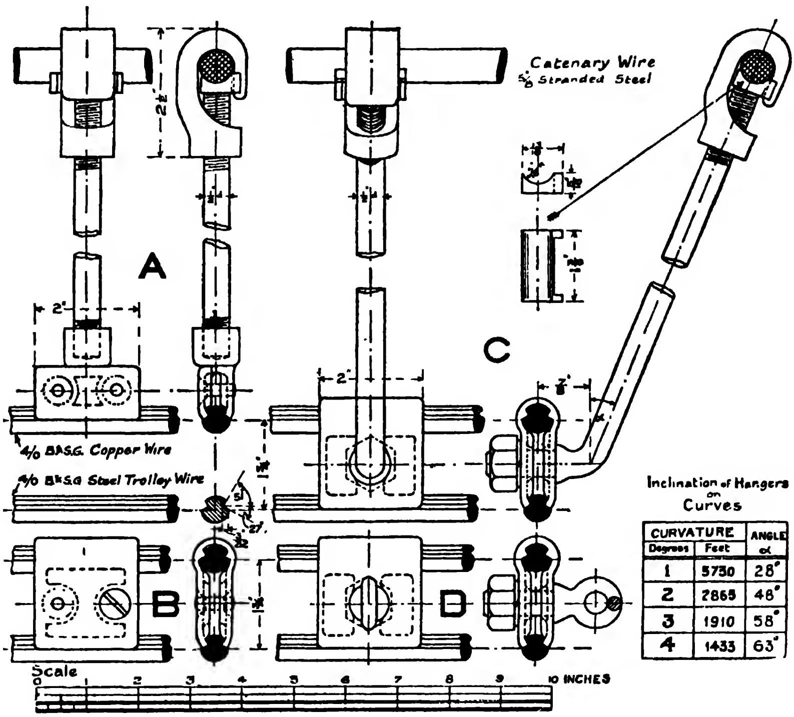
FIG. 434.—Bracket-arm Construction on 11,000-volt Main Lines (New York, New Haven, and Hartford R.R.).

4 mm. (0·158 in.) steel wire: they are connected to the wires by light bronze clips.

The sections of trolley and catenary wires are strained continuously by weights so as to maintain a constant tension of about 1100 lb. in the trolley wires.

At curved track the span is reduced and intermediate pull-off wires are employed where necessary.

Modern single catenary construction on **American main-line** single-phase railways differs in a number of features from that on European railways. For example, (1) the spans are usually longer ; (2) the droppers and clips are much heavier ; (3) the contact wire is either of steel or a special hard-wearing, non-corrosive alloy (phono-electric) which is clipped to a copper wire suspended from the catenary wire, Fig. 433(*a*) ; (4) special inclined hangers, Fig. 433(*b*), are usually employed at curved track to



CURVATURE		ANGLE
Degrees	Feet	α
1	5730	28°
2	2865	46°
3	1910	58°
4	1433	63°

FIG. 435.—Details of Hangers and Clips for N.Y., N.H., and H.R.R. Inclined Catenary Construction. *A*, hanger for straight track ; *B*, intermediate clip ; *C*, inclined hanger for curved track ; *D*, pull-off clip.

enable long spans to be retained without intermediate pull-off wires ; (5) suspension-type insulators are employed in preference to pin-type insulators ; (6) the sections are anchored at both ends, and no devices are employed to maintain a constant tension in the wires.

The supporting structures take the form of structural-steel bracket arms, light gantries, or lattice gantries, according to the number of tracks. The general arrangement of a standard bracket arm is shown in Fig. 434, and details of the hangers are given in Fig. 435.

The normal span is 300 ft. and the sag at 60° F., with normal loading, is 6 ft. 5 in. The catenary wire is of stranded steel $\frac{9}{16}$ in. in diameter ; the contact wire is of alloyed bronze having a cross-sectional area of 0·166 sq. in., and the auxiliary wire is of the same size but of hard-drawn

copper. The hangers are spaced 10 ft. apart and consist of ½ in. galvanized steel rods with malleable-iron clips. The intermediate clips are of bronze. The normal tensions at 60° F. are: catenary wire, 3900 lb.; contact wire, 1815 lb.; auxiliary wire, 1600 lb.

At curved track, special inclined hangers are usually adopted in preference to straight hangers and pull-offs, as by the use of these inclined hangers longer spans are obtained, together with greater flexibility to the trolley wire and the elimination of hard spots. Moreover, the trolley wire can follow more closely the alignment of the track than when straight hangers and pull-offs are employed.* With this inclined construction the catenary wire does not follow the same curve as the trolley wire, and on reverse curves the catenary wire crosses the trolley wire. Fig. 436

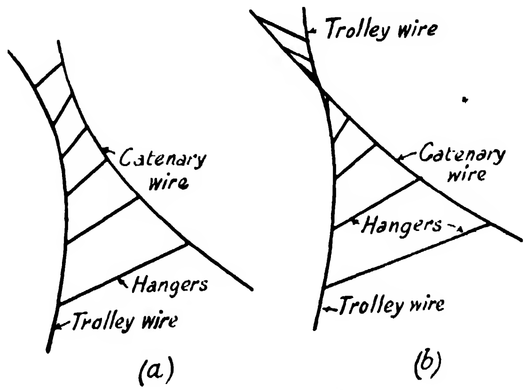


FIG. 436.—Isometric Sketches of Trolley Wires, Catenary Wires and Hangers at Circular (*a*) and Reverse (*b*) Curves.

shows diagrammatically the relative positions of catenary and trolley wires for circular and reverse curves, and Fig. 437 is a view of the construction at a reverse curve.

The hangers are so designed that, when attached to the catenary wire and projecting towards the centre of the curve, the trolley wire will follow the centre of the track. The angle of inclination varies with the radius of the curve, and the length, of course, varies with the position of the hanger. By connecting the horizontal projection of the hanger directly to the clip attached to the trolley and feeder wires, the latter are maintained in a vertical plane. Pull-off wires are only used on curves sharper than 4 degrees (1433 ft.)

Compound catenary construction. This form of construction was originally developed by Messrs. Siemens-Schuckert, to enable automatic tensioning devices to be applied to the trolley wire without causing displacements of the main hangers. The general features are described

* Catenary construction with inclined hangers was developed by the engineers of the New York, New Haven, and Hartford Railroad, with the idea both of eliminating to a large extent the necessity for pull-offs and of increasing the span on curves of moderate curvature. Details of methods of calculation of the lengths of the hangers and other features are given in a paper on "Catenary Design for Overhead Contact Systems," by Mr. H. F. Brown, *Trans. A.I.E.E.*, vol. 46, p. 1082.

briefly on p. 587. This system, with some modifications, is installed on the Lancaster-Heysham-Morecambe (6000-V., single phase) branch of the London, Midland and Scottish Railway, and on the Newport-Shildon (1500-V., direct current) branch of the London and North Eastern Railway.

The general arrangement of the overhead construction on the **Lancaster-Morecambe** line is shown in Fig. 438. The catenary wires consist

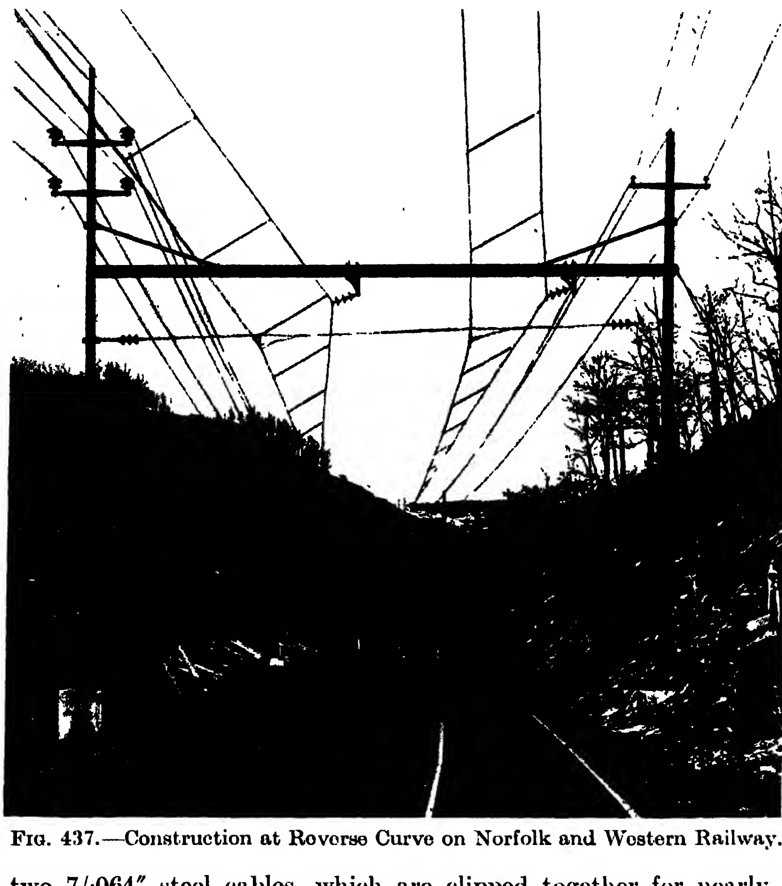


FIG. 437.—Construction at Reverse Curve on Norfolk and Western Railway.

of two 7/·064″ steel cables, which are clipped together for nearly the whole span. At the supporting insulators the wires divide and pass through grooves in a ring fixed to the head of the insulator, so that the catenary wire is free to move longitudinally over a limited distance. The tension between adjacent spans is therefore equalized, and if a break occurs the catenary wires are not pulled down.

From the catenary wire an auxiliary wire (7/·092″ stranded steel) is hung by droppers clipped to each at intervals of 20 ft. The trolley wire—which is of hard-drawn copper of grooved section, equivalent to 0·108 sq. in.—is supported from the auxiliary wire by looped droppers, clipped to the former at intervals of 10 ft. These droppers are all of

uniform length (about 4 in.), while those supporting the auxiliary wire are of variable length, according to their position in the span.

The catenary wires are insulated from the gantries by porcelain

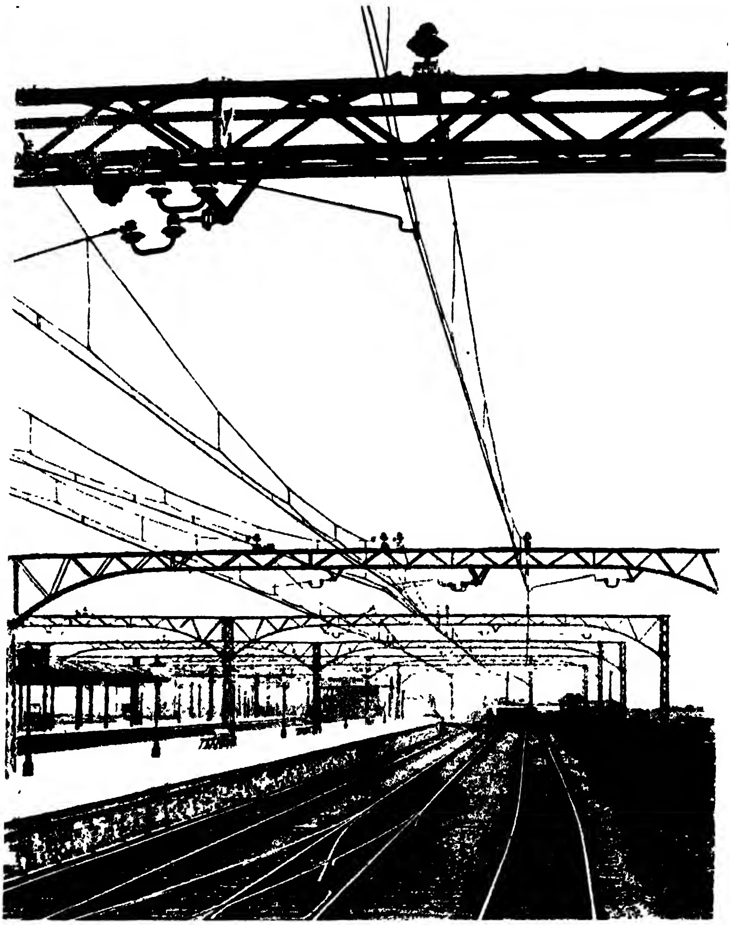


FIG. 438.—Compound Catenary Construction on Morecambe-Lancaster Section of L.M.S. Railway.

insulators of the triple petticoat pin type, supplemented by spool-type insulators on either side.*

At the stations the gantries consist of built-up lattice structures, but at other parts of the line a light structure consisting of two angle-irons carried on wooden poles is adopted.

The trolley wire and the auxiliary wire are anchored laterally at each gantry by a pull-off, which is clipped to the trolley wire and hinged to the gantry. This design of pull-off, together with the loop-type

* The spool type insulators were not included in the original installation.

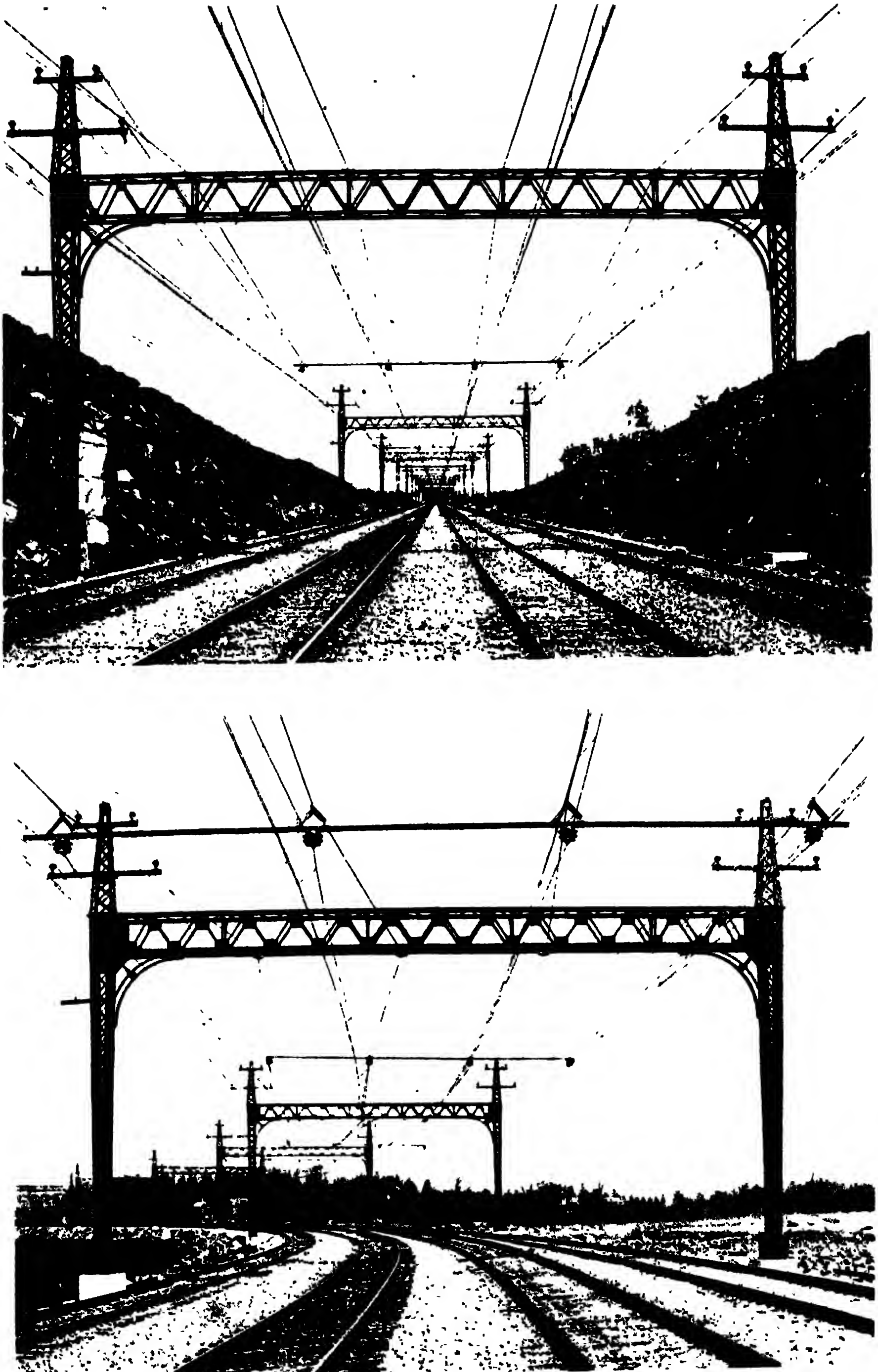


Fig. 439.—Four-track Compound Catenary Construction on Straight and Curved Track (New York–Westchester Section of N.Y., N.H., and H.R.R.).

droppers, allows longitudinal movement of the trolley wire, independent of the auxiliary wire, and does not restrict the flexibility vertically.

In accordance with the standard practice of Messrs. Siemens-Schuckert, the line was originally fitted with automatic tightening devices. This gear has been discarded, as only a very small movement of the weight occurred in practice.

Another form of compound catenary construction is installed on the **Harlem River and Westchester** branches of the New York, New Haven, and Hartford Railroad. Typical views of the construction on straight and curved track are given in Fig. 439.*

Two catenary wires, in addition to the trolley wire and an auxiliary wire, are erected over each track. The upper catenary wire is a $\frac{7}{8}$-in. diameter stranded steel cable, and serves as the main supporting cable for the other wires. It is clamped directly to the top of the gantries, which are spaced 300 ft. apart on straight track and a minimum of 200 ft. on curves. Two 3-in. "I" beams, weighing $5\frac{1}{2}$ lb. per ft., are clamped to each span of the supporting cables so as to span the tracks.

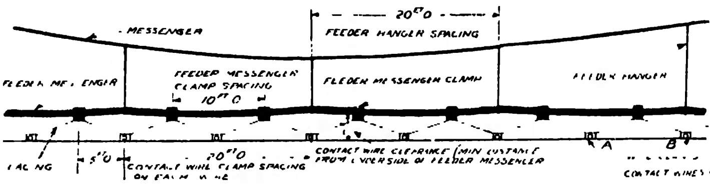


FIG. 440. Compound Catenary Suspension for Heavy Currents, "Laced" Droppers.

These "I" beams are placed 150 ft. apart on straight track, and carry the insulators from which the main catenary wires are suspended. The insulators are of the double petticoat type, and will withstand a dry test of 110,000 volts, the operating voltage being 11,000. The main catenary wire is a $\frac{5}{8}$ in. diameter stranded steel cable, from which a 0·46 in. grooved copper wire is suspended by rigid droppers or hangers spaced 10 ft. apart, the hangers being adjusted so that this wire is horizontal. A 0·46 in. grooved steel wire is used as the trolley wire, and is clipped to the auxiliary wire at points midway between the hangers.

The trolley wires are erected approximately over the centre of each track, and on curves the alignment is maintained by the use of inclined hangers attached directly to the clips.

All the overhead wires are sectionalized at intervals of about three miles, special anchor gantries of heavy construction being installed for the purpose (see Fig. 468, p. 637). The main supporting cables and the catenary cables are anchored to each side of the gantry, while the trolley wires are run through, and are anchored to the catenary wires in the adjoining sections. The trolley wires belonging to the same track are kept a short distance apart when passing under the gantry, and are insulated from the catenary cables to which they are anchored. In this manner a very effective air-insulated section insulator is formed.

* The author is indebted to Mr. W. S. Murray for the photographs of the New Haven electrification. For detailed drawings of the overhead construction see Mr. Murray's paper on "Trunk Line Electrification" (*Trans. A.I.E.E.*, vol. 30, p. 1437).

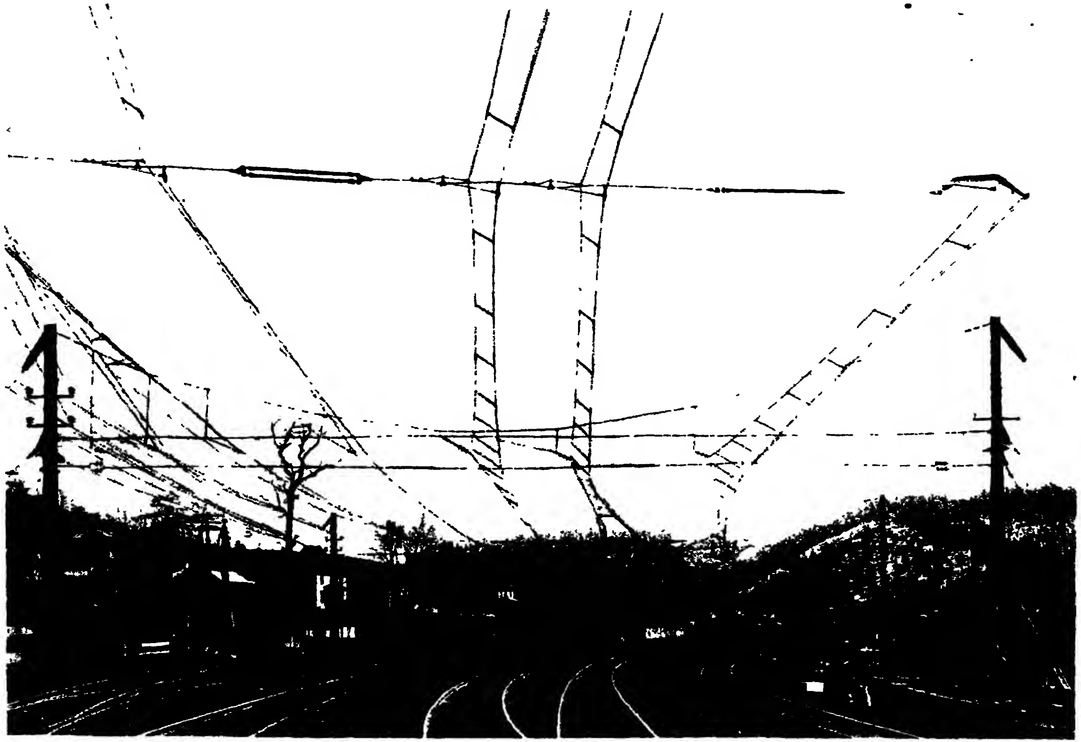


Fig. 441. Cross Catenary Construction at Freight Yard on Norfolk and Western Railway.

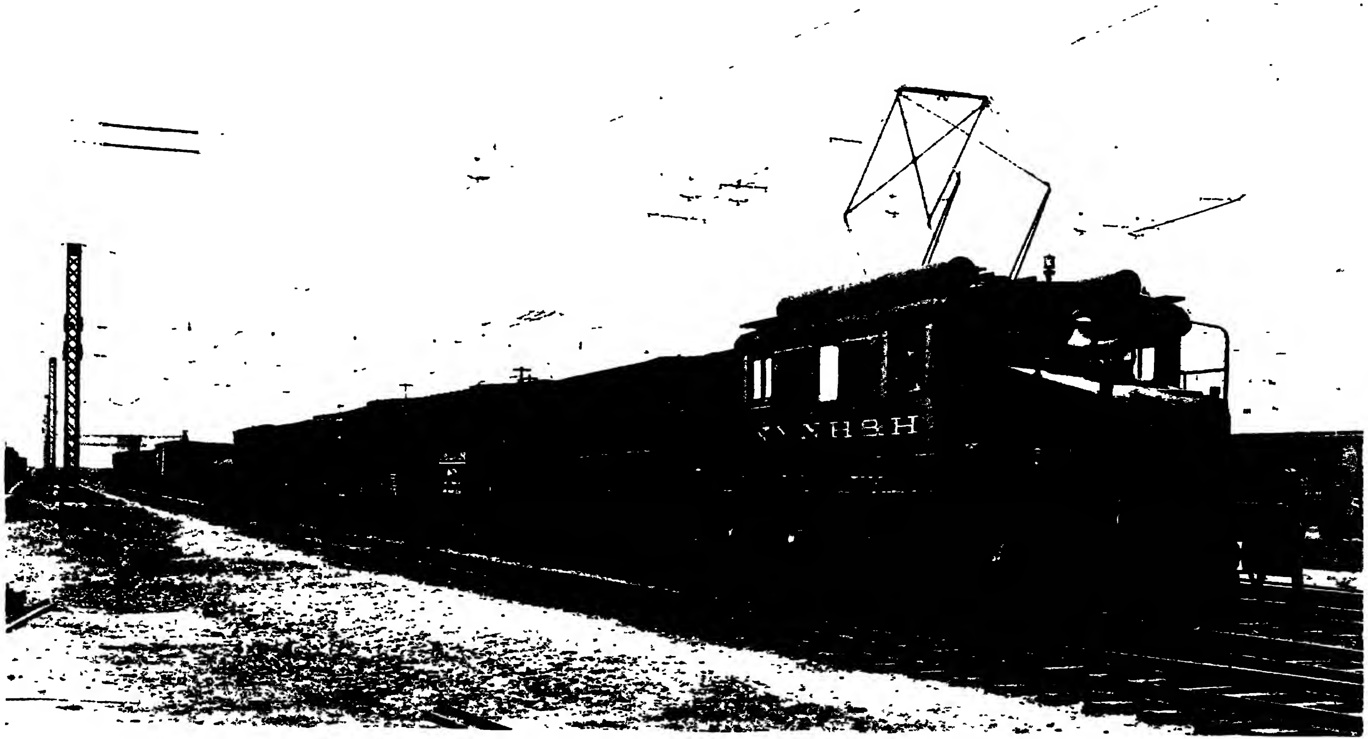


FIG. 442.—Cross Catenary Construction at Large Freight Yard (N.Y., N.H., and H.R.R.).

Compound catenary construction is desirable when **heavy currents** have to be supplied to locomotives. In this case the auxiliary catenary wire is employed as a distributor, and the feeding points can be made suitable for large currents without affecting the flexibility of the trolley wire. Experimental work has been carried out by the General Electric

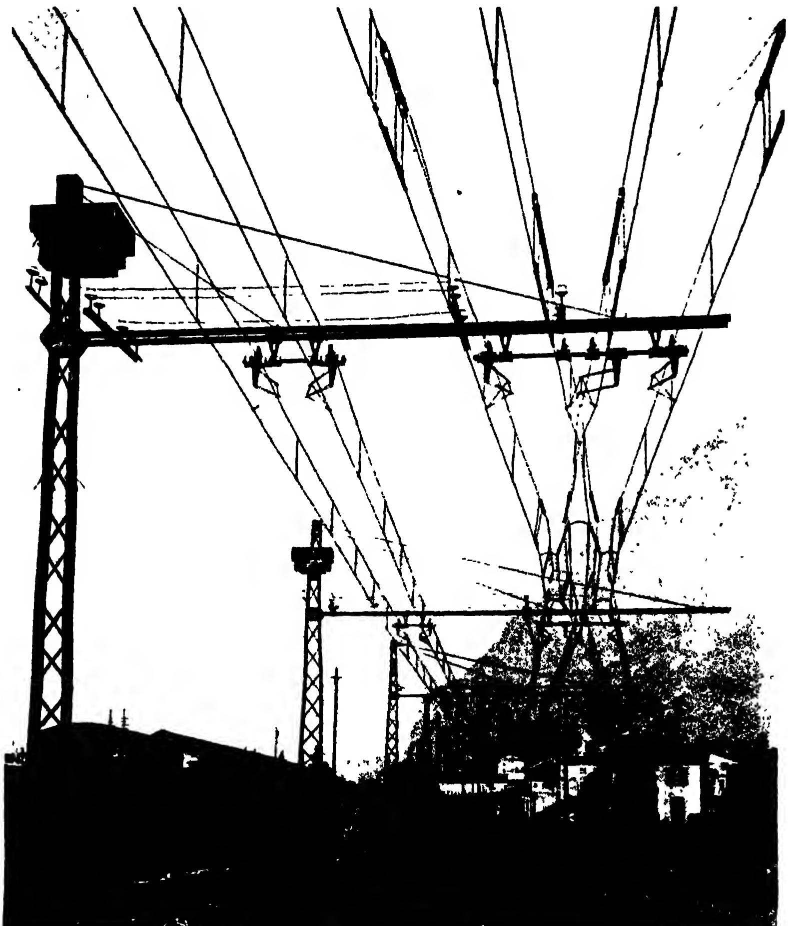


FIG. 443.—Single Catenary Construction on the Italian State Railways.

Co. (Schenectady) to determine the best form of suspension between the auxiliary catenary and the trolley wire.*

The tests indicated that a "laced" suspension (Fig. 440) gave the best results. The flexibility of this suspension was equal to that of a

* A full account of the work is given in a paper on "The Collection of Current from Overhead Contact Wires," by Messrs. Wade and Linebaugh (*Trans. A.I.E.E.*, vol. 46, p. 1114).

compound catenary suspension with loop-type hangers: the laced suspension, however, possessing the additional advantage of a good electrical connection between the auxiliary catenary and the trolley wire at relatively short intervals. The tests demonstrated that with two 0·46-in. trolley wires, arranged in the same horizontal plane, currents of from 2000 to 3000 amperes could be collected sparklessly by a single pantagraph at speeds up to 70 ml.p.h.

Cross catenary construction. In cases where a large number of tracks have to be spanned—e.g. at goods yards, train-shed fanways, etc.—the catenary wires are suspended from transverse span wires, which are erected with considerable sag between towers on each side of the track. By this method, the heavy top girder, which would be required in gantry construction, is dispensed with, but higher towers are necessary on account of the sag in the span wire.

Views of typical cross-catenary construction are shown in Figs. 441, 442, the former illustrating the construction at curved track (on the **Norfolk and Western Railway**), and the latter illustrating the construction at straight track. The view in Fig. 442 shows a portion of the **Oak Point Yard** (of the New Haven Railroad), where approximately 42 miles of track are electrified.

In each case the main catenary insulators are suspended from the span wires by droppers of various lengths, so that the insulators are in the same horizontal plane. Each span wire is provided with turn buckles, which are attached directly to the towers. Lateral stability is obtained by horizontal steady wires, which are insulated from the towers and from the catenary and trolley wires.

Fig. 442 also illustrates some examples of **bow deflectors,** which are necessary at junctions in order to provide a smooth passage for the bow when crossing from one wire to another. The type of deflector shown in the figure consists of a light angle-steel framework, which is supported between the converging trolley wires, so that the lower edges of the longitudinal members are level with the trolley wires. The bow collector is therefore provided with a continuous path of contact, and fouling of the wires is thereby prevented.

Overhead Construction on Three-phase Railways

Fig. 443 is a view showing single catenary construction installed on a section of the **Italian State Railways.** Vertical flexibility of the trolley wire is obtained by a parallel-motion linkwork. This linkwork also provides the necessary lateral stability for the trolley wire.

When the operating voltage does not exceed about 4000 volts, insulated hangers, suspended from span wires in a manner similar to that adopted for side-pole construction on tramways, are practicable. But to avoid too large a sag in the trolley wire short spans must be adopted.

Typical views of the overhead construction on the **Giovi-Genoa** lines of the Italian State Railways are given in Figs. 444 to 446.* These views show clearly the insulated hangers and the method of suspension. Triple insulation is used throughout, and two types of hangers are adopted.

* The author is indebted to the *Tramway and Railway World* for the blocks of Figs. 444, 445, 446.

Fig. 444. A 16 metre Bracket Arm (for four tracks) at Sampierdarena.

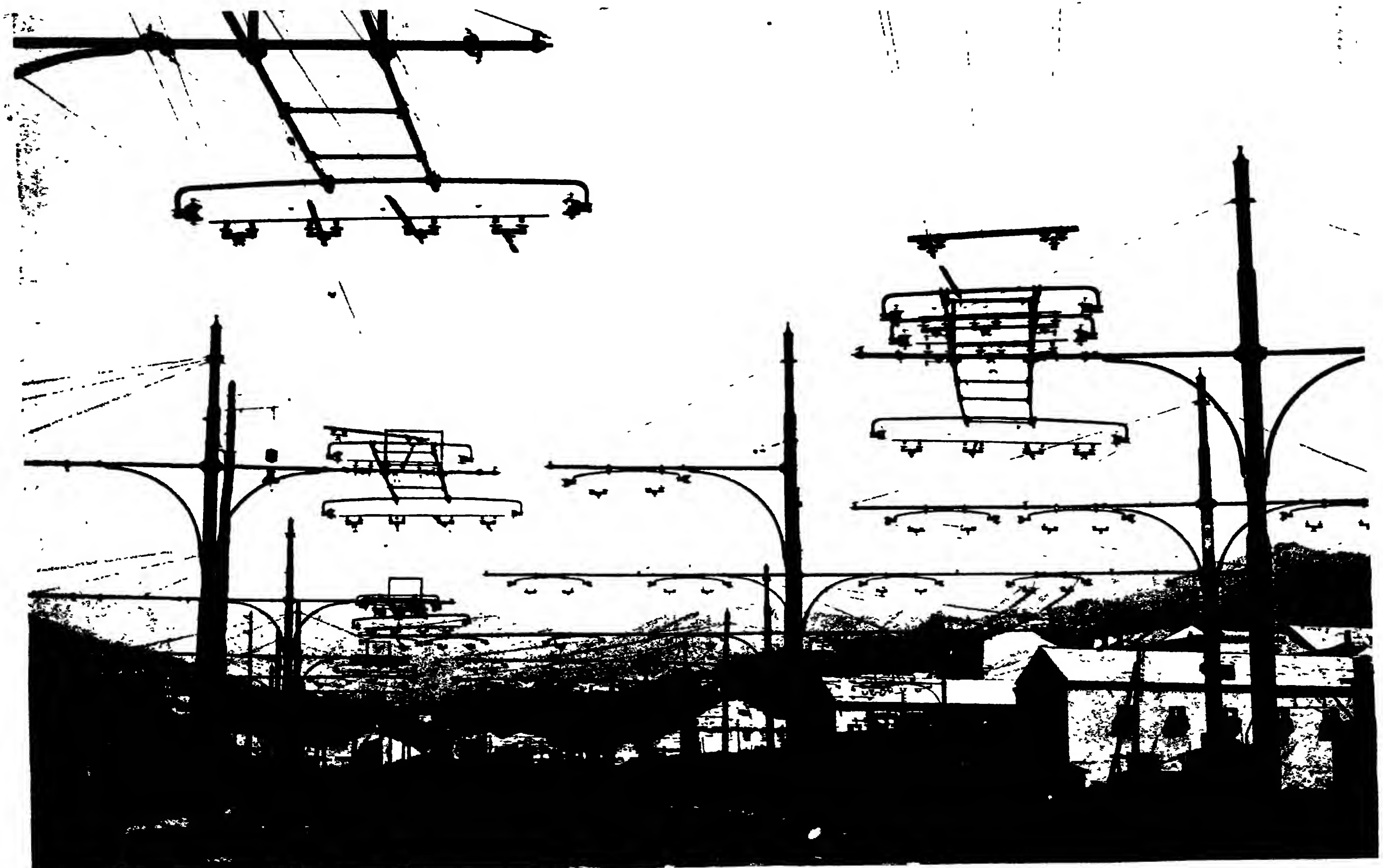


Fig. 446.—Overhead Construction at Group of Tracks at Sampierdarena.

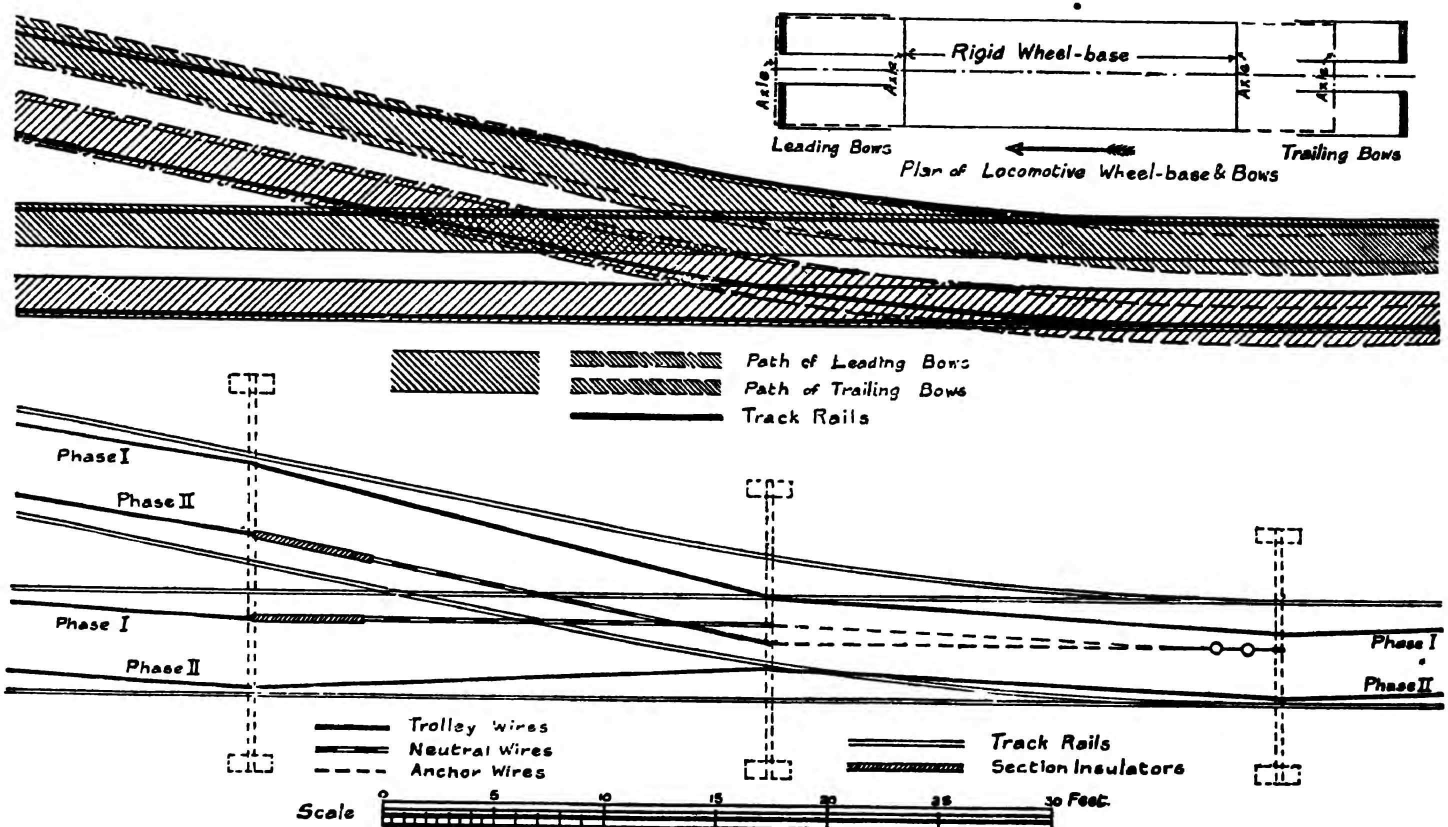


FIG. 447.—Method of Determining Position of Trolley Wires at Junctions on Three-phase Railways.

In three-phase railways the portions of the overhead work requiring the most care in design and erection are **cross-overs** and **junctions.** At these places it is necessary to provide a continuous path for each bow collector, and at the same time prevent a bow from being in contact with wires of opposite polarity. It will be apparent, therefore, that neutral sections and section-insulators are required in addition to live wires.

The positions of the live wires, dead sections, and section insulators can be determined by marking off, on a plan of the track rails, the space swept out by each bow.* If the areas so obtained are marked in a dis-

Fig. 448.—Overhead Construction at Overbridge (Zurich Station, Swiss Federal Railways), showing also International Passenger Train with Oerlikon 2 C 1 Locomotive (1924 type) with Geared Scotch-yoke Drive.

tinctive manner, then it is obvious that dead sections must be inserted where these areas overlap. This may be illustrated by considering the simplest case of a Y-junction on a single track. A plan is first made of the position of the track rails, and the space swept out by each bow is then obtained by the use of a template. The result of this process is represented in Fig. 447. It will be apparent from this diagram that the outer wires may be continuous, but the inner wires must be fitted with section insulators and a dead section where the tracks converge

* This may be done most conveniently by preparing a plan or template (on tracing paper) of the wheel-base of the locomotive or motor-coach with the position and width of each bow marked.

to a single road. The overhead wiring must, therefore, be arranged as indicated. The section insulators generally consist of treated wood, and have a length of about 3 ft.

Overhead Construction at Low Over-Bridges and Tunnels

The minimum height of the trolley wire above the track rails is determined by the minimum clearance allowed above the "loading gauge."

At very low bridges, which have been constructed with the minimum

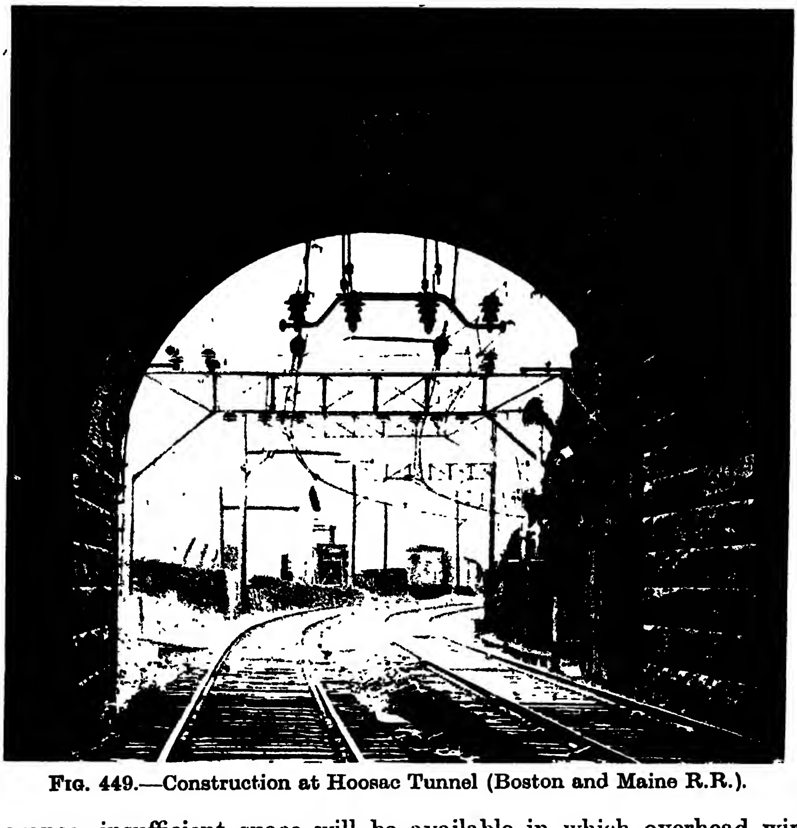


Fig. 449.—Construction at Hoosac Tunnel (Boston and Maine R.R.).

clearance, insufficient space will be available in which overhead wires and their supports can be erected. Therefore either the track must be lowered to obtain the necessary space, or a dead section (which consists of earthed guide wires attached directly to brackets fixed to the bridge) must be installed. In the latter case the trolley wire is dead-ended at each end of the bridge, and a neutral (or insulated) section is inserted between the dead wires and the trolley wires to provide a continuous path for the bow.

At bridges where the necessary space is available for the erection of overhead wires, the design of the supports for the insulators, etc., will be influenced largely by local conditions. In cases where the width of

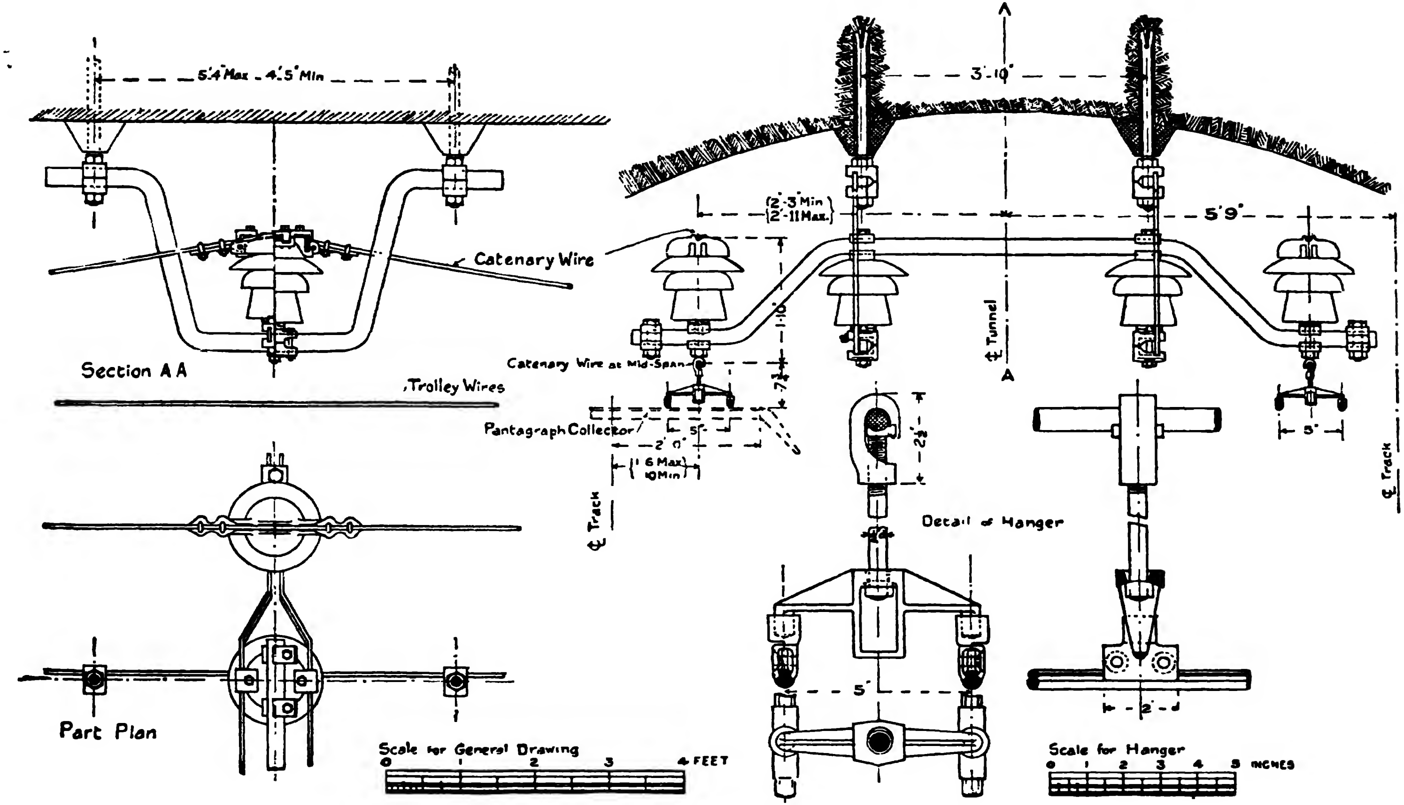


FIG. 450.—Details of Construction Hoosac Tunnel.

the bridge is not great, an insulated framework can be fitted to the underside of the bridge, as shown in Fig. 448.

In all cases where live wires have to be taken under bridges, etc., the gradient between the two levels of the trolley wire must be such that the bow will remain in contact with the trolley wire at all speeds, otherwise considerable flashing will occur. With the ordinary type of bow collector, a gradient of 1 in 50 is satisfactory at speeds of 40 ml.p.h., but at higher speeds and with a pantagraph collector the gradient must be limited to about 1 in 100.

Fig. 449 shows the application of the single catenary system to a double-track tunnel. This particular construction is installed in the Hoosac Tunnel (on the Boston and Maine Railroad), which is 25,080 ft. (4·75 miles) long. Traffic is handled by electric locomotives supplied with single-phase current at 11,000 volts. The electric locomotives are coupled to the steam locomotive, and haul the complete train through the tunnel.

The trolley wires for each track consist of two 0·46-in. grooved "phono-electric" wires, suspended, in the same horizontal plane, from a stranded copper catenary wire ($\frac{5}{8}$ in. in diameter) by bronze hangers of the type shown in Fig. 450. The copper catenary wire (which is continuous throughout the tunnel) acts also as a feeder.

The catenary wire is supported at intervals of about 100 ft. on triple petticoat porcelain insulators, the corresponding insulators for each track being fixed to a framework supported by a pair of similar insulators (Fig. 449). The latter insulators are fixed to stirrups, which are bolted to the crown of the tunnel. In order to obtain sufficient clearance, the catenary wires are placed 14 in. inside the centre of the track. Each insulator will withstand a dry test of 150,000 volts, and two insulators are in series between the trolley wire and ground. This high factor of safety was considered desirable on account of the length of the tunnel and the large quantity of moisture present. As the insulators form the most important link in the overhead construction, it is good policy to adopt a high factor of safety, especially in a long tunnel. Moreover, it has been stated* that an insulator to withstand 150,000 volts only costs about four shillings more than one to withstand 40,000 volts.

* *Trans. A.I.E.E.*, vol. 30, p. 1437. Paper by Mr. W. S. Murray on "Trunk Line Electrification." Mr. Murray has informed the author that the cost of insulators for a given length of main-line construction (of the type illustrated in Fig. 439) is only 1·75 per cent of the total costs of the overhead construction. It is, therefore, poor policy to attempt to cut down the size of the insulators on main-line electrifications.

In connection with the costs of overhead construction for main lines see a paper by Mr. E. J. Amberg on "Overhead Contact Systems—Construction and Costs" (*Trans. A.I.E.E.*, vol. 34, p. 1459).

CHAPTER XXVI

FEEDING AND DISTRIBUTING SYSTEMS FOR TRAMWAYS AND RAILWAYS

WHEN electrical energy has to be supplied from a power station (or a substation) to a number of circuits at a constant voltage, the various circuits must be connected to distributing cables (called *distributors*), which are fed at suitable points (called *feeding points*) by other cables (called *feeders*). The latter cables connect the feeding points of the distributors to the station bus-bars, and their function is to maintain these points of the distributors at a definite voltage. The function of the distributors is to supply the circuits at practically constant voltage. This difference in the functions of distributors and feeders has an important effect upon the design of these cables.

Thus, in the design of a distributor, the principal consideration is the permissible variation of voltage along the distributor. On the other hand, a feeder should be designed for minimum annual operating expenses, which include the cost of the losses in the cable, together with the interest and depreciation charges.

Traction distributing system. In electric traction systems the trolley wires and track rails—or, alternatively, the two sets of conductor rails—form the distributors. The loads are represented by the currents taken by the cars or trains, and are variable not only in magnitude but also in position.

In **tramways** the distributing system must conform to certain statutory regulations, chief among which are the following—

(1) The voltage at the trolley wire shall not exceed 550 volts ; and that at the generating station (or sub-station) shall not exceed 650 volts.

(2) The trolley wire shall be divided into sections not exceeding one half-mile in length.

(3) The potential difference between any two points of the (track) rail return system shall not exceed 7 volts.

Therefore, to comply with these regulations, separate feeding systems will be required for the trolley wire and the track rails.

In direct-current railways using the track rails as a return, the potential difference in the track rails must also be maintained within the 7-volt limit in order to avoid disturbing the working of telegraphic apparatus by earth currents. The positive portion of the distributing system, however, has not to conform to statutory regulations with respect to voltage regulation and sectionalization at every half-mile.

On account of the low voltage drop in the track rails, the variation of voltage at the cars in overhead systems depends almost entirely upon the voltage drop in the trolley wire. In any given case the permissible variation of voltage must obviously depend upon service conditions, and the minimum voltage must be such that the schedule speed can be maintained under all conditions of traffic. In some cases a maximum

voltage variation of 10 per cent may be permissible, but in other cases—particularly in central districts with heavy traffic—a lower maximum variation will generally be desirable.

Length of trolley wire between feeding points. The determination of the feeding points for a traction distributor is not so straightforward as that for a lighting distributor, on account of the loads being variable both in magnitude and position. Moreover, in practice, occasional blocks in the traffic will occur, with the result that the number of cars on one distributing section may be much greater than that under normal conditions of traffic. Hence a certain amount of judgment must be exercised in deciding upon the feeding points, and each case must be considered separately.

The permissible length of trolley wire between two feeding points may be determined when the voltage drop corresponding to normal conditions is fixed, and when the current and particulars of the trolley wire are known. For tramway traffic, the normal operating conditions may be considered to correspond to uniform spacing of the cars along the track. The current in a distributing section is obtained from a knowledge of the number of cars on the section and the current per car (the average value of which may be assumed to be between 15 and 30 amperes, according to the type of car, equipment, and service).

Thus, suppose the normal conditions correspond to a $2\frac{1}{2}$-minute service of cars operating at a schedule speed of 8 ml.p.h., the average current per car being 20 amperes, and that a drop of 20 volts is permissible in the trolley wire (which is a single 0·348 in. hard-drawn copper wire, having a resistance of 0·46 ohm per mile).

The average distance between consecutive cars $= 2{\cdot}5(60/8) = \frac{1}{3}$ ml., and the resistance of the trolley wire between these cars $= \frac{1}{3} \times 0{\cdot}46 = 0{\cdot}153$ ohm.

Hence the voltage drop in a 1-mile length of trolley wire

$$= 0{\cdot}153 \times 20(3 + 2 + 1) = 18{\cdot}4 \text{ volts*}$$

and that in a $1\frac{1}{3}$ mile length

$$= 0{\cdot}153 \times 20(4 + 3 + 2 + 1) = 30{\cdot}6 \text{ volts.}$$

Therefore the length of a distributing section is $20/18{\cdot}4 = 1{\cdot}09$ mile ;

* In a distributor fed from one end and loaded with a number of loads, the voltage drop is calculated as follows:—

Let I_1, I_2, I_3, etc., denote the load currents in amperes ; L_1, L_2, L_3 . . . denote the distances of the loads from the feeding points ; l_2, l_3 . . . denote the distances between consecutive loads, l_2 representing the distance between the loads I_1 and I_2, etc. Then if r denotes the resistance of unit length of the distributor, the voltage drop (v) from the feeding point to the nth the load will be

$$v = r\{L_1(I_1 + I_2 + I_3 + \dots I_n) + l_2(I_2 + I_3 + \dots I_n) + l_3(I_3 + \dots I_n) + \dots l_n I_n\}$$
$$= r(L_1I_1 + L_2I_2 + L_3I_3 + \dots L_nI_n),$$

since $L_2 = L_1 + l_2$; $L_3 = L_1 + l_2 + l_3$; etc.

In the special case when the loads are all equal and occur at equal distances along the distributor, we replace

$$I_1, I_2, I_3 \dots \text{ by } I, \text{ and } L_1, l_2, l_3 \dots \text{ by } l,$$

and obtain

$$v = rlI(n + (n-1) + (n-2) + \dots 1) = rlI \times \tfrac{1}{2}n(n-1)$$

in which n denotes the number of loads.

but, as the trolley wire has to be sectionalized every half-mile, the length of a distributing section would be made equal to 1 mile.

Feeders. If the feeding points of the distributors are maintained at constant voltage, the voltage drop in the feeders will have no effect upon the voltage variation in the distributors. Hence, under these conditions, the voltage drop in the feeders may be selected at a value which will result in the most economical operation.

Now the annual cost of a feeder comprises the cost of the energy dissipated, together with the interest and other charges on the capital expenditure. The latter can be divided into two portions, one being uninfluenced by the cross-sectional area of the cable and the other being directly dependent upon the cross section. For example, the costs of excavations, etc., laying of ducts and drawing-in will depend only upon the length of cable and the number of cables being laid. Similarly, a portion of the cost of the insulation will be independent of the cross-section of the cable.

Therefore, let the cost per mile of the cable, laid and jointed, be $(£)C = (A + Ba)$, where a denotes the cross-section of the cable, B the portion of the capital cost which is dependent on the cross-section, and A the remaining portion of the capital cost, which is independent of the cross section.

Then, if m is the percentage interest and depreciation charges on the capital cost of the completed cable, the annual charges per mile are

$$0{\cdot}01m(£)C = 0{\cdot}01m(A + Ba)$$

If I is the r.m.s. value, in amperes, of the current over a period of h hours per annum, the annual cost, $£(E)$, of the I^2R losses in a cable 1 mile long and cross-section a sq. in. is given by

$$(£)E = I^2(0{\cdot}0425/a) \times ph/240{,}000$$

where p is the price, in pence, of a Board of Trade unit (i.e. 1 kW. hour) delivered to the cable, which may usually be taken as the price per unit delivered to the switchboard.

[NOTE—The numeral factor 0·0425 refers to the resistance of a copper cable 1 mile long and 1 sq. in. in cross section.]

Therefore the annual cost of the cable is

$$0{\cdot}01m(£)C + (£)E = 0{\cdot}01m(A + Ba) + 0{\cdot}0425(I^2ph/a)/240000,$$

which will be a minimum when

$$0{\cdot}01mBa = 0{\cdot}0425(I^2ph/a)/240000$$

Whence $\qquad I^2/a^2 = (mB/ph) \times 5{\cdot}64 \times 10^4$

or I/a (i.e. the current density $= 237{\cdot}5\sqrt{(mB/ph)}$ . . . (57)

Hence the **most economical current density** is that which makes the annual cost of the losses in the cable equal to the variable portion of the annual charges on the capital cost.* But if this current density exceeds that corresponding to the limiting operating temperature of the cable, the cross section must be chosen on the latter basis.

It is important to note that the voltage drop in the feeder does not appear in the above expression, although, when the current density is determined, the voltage drop is also indirectly determined.

Cases will arise with long feeders when the voltage drop, corresponding

* This relationship is usually known as Kelvin's law.

to the most economical current density, will be excessive, and in these circumstances either the cross section must be increased to give a lower voltage drop, or a booster must be used in conjunction with the cable.

The booster for this purpose consists of a self-excited series generator connected in series with the cable, the generator being designed with a "straight-line" characteristic (i.e. the terminal voltage is directly proportional to the current). This machine may be driven either from one of the main generators or by a separate shunt motor.

The booster set, however, has losses and capital charges, which are additional to the operating costs of the cable. Whether or not a larger cable should be employed, or a booster should be installed in conjunction with the original cable, will depend upon the total annual costs in the two cases.

In obtaining the **total annual costs for a "boosted" cable,** the losses in the booster may be allowed for by increasing the cost per kW.-hour delivered to the cable, and the annual charges on the booster may be added to the annual charges on the cable. But the increase in the cost of energy delivered to the cable, combined with the additional annual charges on the booster set, must be allowed for in determining the most economical current density. Hence the above equation must be modified as follows—

If p denotes the cost (in pence) of 1 kW.-hour at the switchboard, and η is the efficiency of the booster set at the average working load, then each kW.-hour of boosted energy delivered to the cable will cost p/η on account of the losses in the booster set. Again, if (£)X denotes the capital cost of the booster set per kW. output, n denotes the percentage interest and depreciation charges per annum, and (£)Y denotes the cost of attendance and maintenance per kW. output per annum, then the charges on the booster set per kW. output per annum will be $240(0{\cdot}01nX + Y)$ *pence*. Hence, if the booster is in service h hours per annum, the charges per kW.-hour will be $240(0{\cdot}01nX + Y)/h$ *pence*, and the total cost of 1 kW.-hour delivered to the cable will be

$$[p/\eta + 240(0{\cdot}01nX + Y)/h] \text{ pence.}$$

Therefore, the annual cost of the boosted cable (of cross-section a' sq. in.) will be

$$0{\cdot}01m(A + Ba') + \frac{I^2h}{a'} \times \frac{0{\cdot}0425}{240000} \times \left\{\frac{p}{\eta} + \left(\frac{0{\cdot}01nX + Y}{h}\right)240\right\}$$

Whence, the most economical current density (I/a') is given by

$$\frac{I}{a'} = 237{\cdot}5\sqrt{\frac{mB}{h[(p/\eta) + 240(0{\cdot}01nX + Y)/h]}} \qquad . \qquad . \qquad (58)$$

Examples. (1) Determine the most economical cross-section for an unboosted feeder, 1 mile long, which is in service 15 hours per diem, the r.m.s. value of the current during this period being 150 amperes. The variable component of the cost of the completed paper-insulated cable may be taken at £85 per ton of copper: the interest and depreciation charges are 7 per cent, and the cost of 1 kW. hour delivered to the cable is 0·6 pence.

As the weight of copper in a 1-sq. in. cable, 1 mile long, is 9·1 tons, the term B in equation (57) is ($9{\cdot}1 \times 85 =$) 774. Hence

$$I/a = 237{\cdot}5\sqrt{[7 \times 774/(15 \times 365 \times 0{\cdot}6)]} = 305 \text{ A. per sq. in.}$$

The cross section corresponding to this current density is (150/305 =)

0·492, say 0·5, sq. in., for which the safe continuous working current is 540 A.

The voltage drop corresponding to the r.m.s. current is (150 × 1 × 0·0425/0·5 =) 12·75 V., and if the maximum current is 2·5 × r.m.s. current the maximum voltage drop will be (2·5 × 12·75 =) 31·9 V.

(2) Determine the most economical cross section for a boosted cable, 2 miles long, which is in service 15 hours per diem, the r.m.s. value of the current during this period being 150 A. The capital cost of the booster set (including switchgear) may be assumed as £15 per kW. output, on which the interest and depreciation charges are 12 per cent per annum. The cost of attendance and maintenance may be assumed as £0·4 per kW. output per annum.

Assuming the efficiency of the booster set at the load corresponding to the above r.m.s. current to be 75 per cent, and substituting in equation (58), the most economical current density for this boosted feeder is

$$\frac{I}{a'} = 237{\cdot}5 \sqrt{\frac{7 \times 2 \times 9{\cdot}1 \times 85}{15 \times 365\,[(0{\cdot}6/0{\cdot}75) + 240\,(0{\cdot}01 \times 12 \times 15 + 0{\cdot}4)/15 \times 365}}$$
$$= 353 \text{ A. per sq. in.}$$

The cross section corresponding to this current density is (150/353 =) 0·425 sq. in. A 0·4 sq. in. cable would be employed.

The voltage drop corresponding to the r.m.s. current is (150 × 2 × 0·0425/0·4 =) 32 V., and that at the maximum current (i.e. 2·5 × r.m.s. current) is (2·5 × 32 =) 80 V.

If the bus-bar voltage is 25 volts higher than the voltage at the feeding points, the maximum voltage required from the booster will be (80 − 25 =) 55 volts. Hence the maximum rating of the booster is

(55 × 150/1000 =) 8·25 kW.

These examples show that an extensive tramway system, with heavy traffic, will require a number of boosted feeders for the positive distributing system when the supply is given from a central power station. In many cases it may not be possible to supply the system economically in this manner, and in these cases the low-tension distributing system must be supplied from a number of substations, which may be located in the immediate neighbourhood of the distributing sections, so that only short feeders are required.

Positive Feeding and Distributing Systems for Tramways

The method of feeding the distributing sections of the trolley wire will be influenced largely by traffic and economical considerations.* In districts with very heavy traffic, the traffic considerations will usually preponderate, and the feeding system must be arranged so that the opening of a feeder circuit breaker at the generating station or substation will only affect a small portion of the traffic. Under these circumstances a separate feeder is desirable for each half-mile section of the trolley wire, and these feeders must be supplied from substations.

In cases of extremely heavy traffic the conductivity of the half-mile sections of the trolley wire may require to be increased by continuing the feeder, or another auxiliary feeder (which may consist of an additional trolley wire), along the section and tapping the trolley wires to the

* For detailed examples of the design of the feeding and distributing system see a paper by Mr. Henry M. Sayers on "The Calculation of Distributing Systems for Electric Traction under British Conditions" (*Journ. I.E.E.*, vol. 29, p. 692).

auxiliary feeder at frequent intervals. But with conduit tramways the relatively large cross-section of the conductor rails provides sufficient current-carrying capacity for the heaviest conditions of tramway traffic, and auxiliary feeders are unnecessary.

On the other hand, with light traffic, considerations of economy become of greater importance, and several half-mile sections of the trolley wire must be supplied from a single feeder. Two methods are shown diagrammatically in Fig. 451. In these diagrams the section insulators in the trolley wire are indicated, as well as the "section" and "feeder

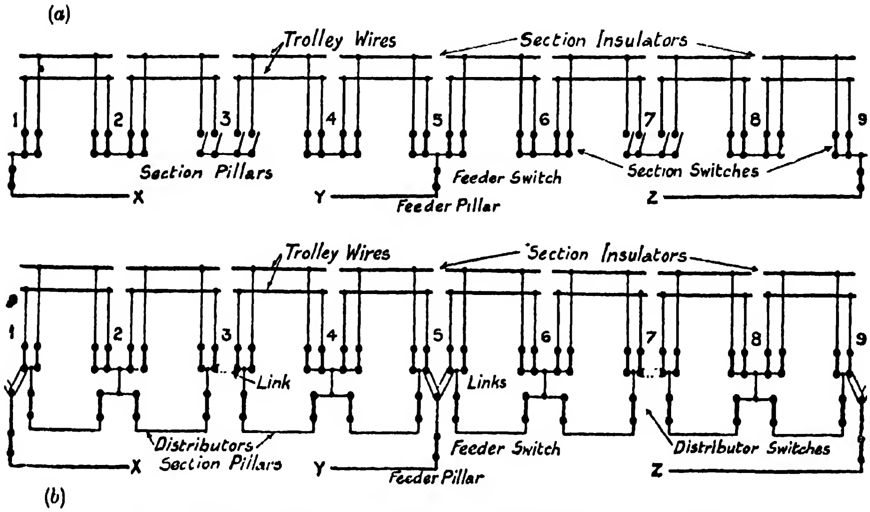


FIG. 451.—Methods of Feeding and Sectionalizing Trolley Wires for Tramways.

pillars,"* which contain the switches for isolating the sections of the trolley wire.

In one case the trolley wire is used as a distributor, and each distributing section comprises two or more half-mile lengths of trolley wire. In the other case (which permits the use of a smaller number of feeders), feeders of large cross section are run to a few points in the system, from which the current is distributed to the various half-mile sections of the trolley wire by means of graded distributing cables. This method is more economical in copper than the first method, as longer distributing sections are obtained. Moreover, the variation of voltage between adjacent half-mile sections of the trolley wire is smaller than that for the first method.

On the other hand, in the event of the feeder circuit breaker opening, or a breakdown of the feeder occurring, the second method results in a greater temporary interruption of traffic than the first method. But, in the case of a breakdown of the feeder, the supply can be maintained to either side of the feeding point through the distributors connected to the adjacent feeders, although this may result in the overloading of some of the distributors.

The methods of maintaining continuity of service—due to, say, a

* Feeder and section pillars are discussed on p. 626.

breakdown of a feeder—in the two cases are of interest. Thus, suppose a fault occurred on feeder Y. With the system of Fig. 451(a) feeder pillar No. 5 would be visited first, and the feeder switch opened. Section pillars Nos. 3 and 7 would then be visited, and the section switches in these pillars would be closed, thereby dividing the load of feeder Y between feeders X and Z. In some cases it may be desirable to open the section switches in pillar No. 5.

With the system of Fig. 451(b), feeder pillar No. 5 would be visited first, and the links interconnecting the distributor and feeder switches would be removed. Feeder pillars Nos. 3 and 7 would then be visited, and the distributor switches would be connected together by a link, as indicated in Fig. 451. One half of the section normally supplied from

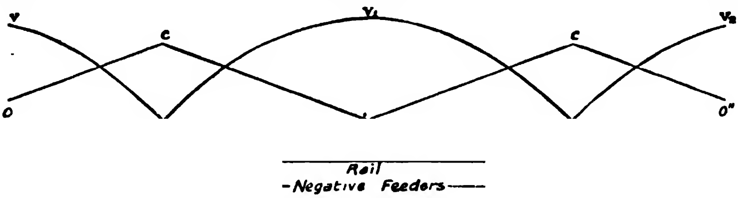


FIG. 452.—Variation of Voltage along Rail with Uniform Current Loading.

feeder Y is then transferred to feeder X, while the other half of the section is transferred to feeder Z.

NEGATIVE FEEDING AND DISTRIBUTING SYSTEMS FOR TRAMWAYS

Voltage drop in rails. The exact calculation of the voltage drop in the track rails is complicated on account of leakage currents due to the rails being uninsulated. For instance, a portion of the return current may reach the station via the earth, and the earth may also act as a diverter (or shunt) to the track rails, thereby relieving the rails of some of the return current. Although it is possible to calculate the voltage drop in the track rails under the latter conditions,* it is preferable to neglect the effect of the conductivity of the earth, and to design the distributing sections so that the voltage drop under the worst conditions does not exceed the statutory limit of 7 volts.

If the current in the rails is due to a number of cars, equally spaced along the track, the voltage drop in a length of the track rails can be calculated by a method similar to that adopted for the trolley wire. In determining the resistance of the rails, the resistance of the bonded, or welded, joints must be included; but if the cross-bonding occurs at frequent intervals, the individual track rails may be considered as being permanently connected in parallel. For example, the resistance of 1 mile of B.S.S. No. 7 tramway rail (including resistance of bonded joints) is 0·047 ohm, and therefore the resistance of 1 mile of double track may be considered to be 0·012 ohm.

The average voltage drop in the rails under normal conditions should be assumed at a value not in excess of 5·0 volts, in order to allow for possible future developments of the tramway system, as well as the effects of blocks in the traffic, and "bunching" of the cars at certain parts of the system.

* See *The Electrician*, vol. 45, p. 595.

With the voltage drop given, and the resistance of the track known, the length of the rail distributing sections can be determined from a knowledge of the electric loading. In many cases it is convenient to consider that the loading is uniformly distributed throughout the distributing section (i.e. the current decreases uniformly from the feeding point), so that the voltage drop along the section follows a parabolic law.* The length of a distributing section corresponding to a definite voltage drop is then readily determined, and the position of the feeders naturally follows. As the rails are continuous throughout the system, the curve of voltage drop between adjacent feeding points will be a parabola with the zero points at the feeding points. Fig. 452 represents these conditions, the straight lines *o c o′ c o″* representing the distri-

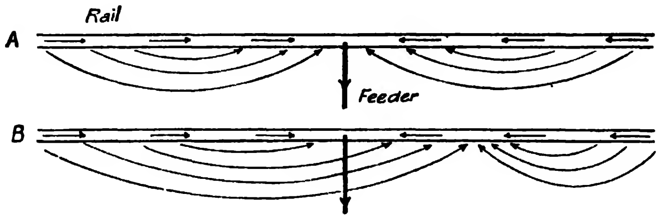


FIG. 453.—Distribution of Leakage Currents. *A*, equally loaded rail sections ; *B*, unequally loaded rail sections.

bution of current along the rail, and the parabolas $v\ x\ v_1\ y\ v_2$ the variation of the voltage drop ; the feeding points $x\ y$ being at the same potential.

Now the feeders connect the points x, y of the rails to the negative bus-bar, and, therefore, with *uniform electric loading* of the rail sections, the feeders must be *designed for the same voltage drop*. Hence, when long and short feeders are in use on the same system, equality of voltage drop in the several feeders must be obtained either by connecting resistances in series with the short feeders, or by neutralizing a portion of the voltage drop in the long feeders by means of boosters.†

Of these methods, the more economical one for given conditions will depend upon the relative values of the operating costs with resistances and with boosters.‡ But when series resistances are employed the voltage drop in the feeders and resistances affects the voltage variation at the cars and must, therefore, be taken into account in computing the operating costs. On the other hand, with boosted feeders,

* If i is the rate of increase of the current along the rail from the dividing point (where the current is zero) and r is the resistance of unit length of the rail, then the current at any point, distant x from the dividing point, will be ix, and the voltage drop in an element of rail length dx will be $ix\ r\ dx$. Hence the voltage drop (v) in a length L from the dividing point will be given by

$$\int_0^L ix\,r\,dx = ir\left[\frac{x^2}{2}\right]_0^L = \tfrac{1}{2}irL^2$$

Thus v is proportional to L^2, and the curve connecting v and L is a parabola.

† Boosters used in this manner (with negative feeders) are called *negative boosters*.

‡ In this connection see *The Electrician*, vol. 73, p. 607, where comparative costs have been calculated for the two cases by Mr. H. M. Sayers.

the resultant voltage drop between rails and negative bus-bar may be adjusted (within limits) to any value desired, including zero.

Ideal conditions. The ideal conditions for a negative feeding system are represented diagrammatically in Fig. 452. The voltage drop along each distributing section of the rails is the same throughout the system, and, consequently, there is no tendency for leakage currents to pass between the sections. If the conductivity of the earth is uniform throughout the sections, the distribution of the leakage currents will be as indicated in Fig. 453(*a*). On the other hand, if the voltage drops are unequal, there is an interchange of leakage current between adjacent sections as indicated in Fig. 453(*b*). Hence, to prevent the interchange of leakage currents when adjacent sections are unequally loaded, the voltage drops must be equalized by adjusting the lengths of the sections

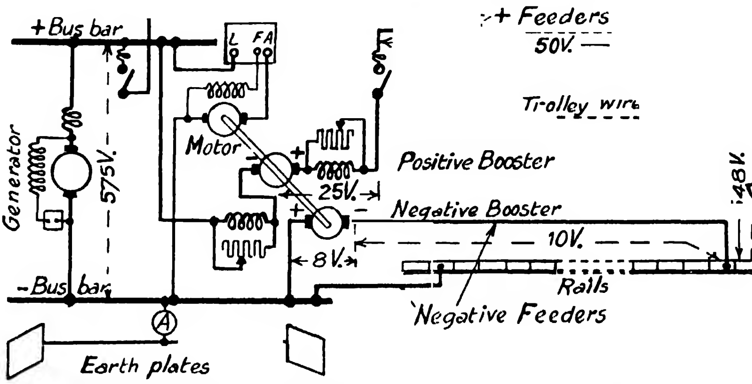


FIG. 454.—Connections of Feeders and Boosters in Tramway System. (Typical Circuit Voltages and Voltage Drops are Indicated.)

in the inverse ratio of the square roots of the loading. Thus, if I_1, I_2 denote the intensity of the loading (amperes per mile) in sections of lengths L_1, L_2 respectively, then $\frac{1}{2}I_1rL_1^2 = \frac{1}{2}I_2rL_2^2$, or $L_1/L_2 = \sqrt{(I_2/I_1)}$, where r denotes the resistance per mile of track.

Therefore, a large tramway system, supplied direct from a central power station, will require boosters for the negative feeding system as well as for the positive feeding system.

Connections of boosters. Although the boosters for the positive and negative feeders are series machines, with similar characteristics, the methods of operating them are different. Thus, the positive boosters are operated self-excited. The negative boosters, however, are separately excited ; the armature being connected in series with the negative feeder, and the field winding being connected in series with the positive feeder supplying the corresponding sections of the trolley wire. The " boost " on the feeder is adjusted by means of a diverter rheostat connected in parallel with the field winding. Fig. 454 shows the connections.

FEEDER AND SECTION PILLARS FOR TRAMWAYS

(1) **Overhead tramways.** The sectionalizing of the distributing system is carried out by means of switches located in feeder and section pillars, which are placed in convenient positions adjacent to the track.

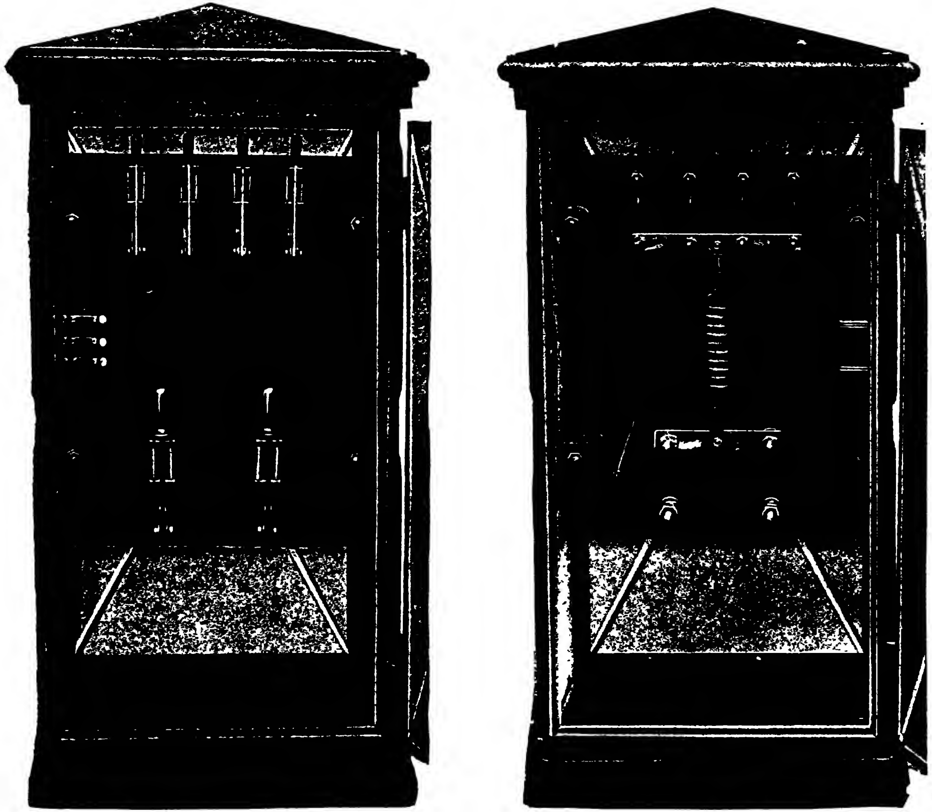


FIG. 455.—Front and Back Views of Section Pillar (British Insulated Cables).

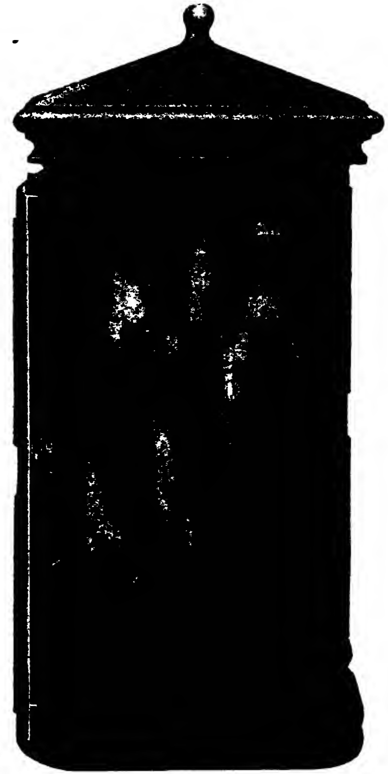


FIG. 456.—Section and Feeder Pillar (Brecknell, Munro, and Rogers).

With the ordinary type of section insulator (Fig. 416, p. 576), a section pillar is required at every half-mile of the route; the pillar containing the switches for disconnecting the sections of the trolley wire from one another and from the feeder or distributor.

Typical section pillars are illustrated in Figs. 455, 456. In the pillar shown in Fig. 455 (which is suitable for any of the intermediate section pillars in the graded distributor method of distribution shown in Fig. 451(*a*)), the four switches on the upper portion of the panel control the adjacent sections of the trolley wire for the "up" and "down" tracks, and the two lower switches control the distributors which supply these sections. The two sets of switches are connected through a choking coil (as shown in the view of the back of the panel): the trolley switches are also connected to a lightning arrester, which can be seen on the right-hand side of the back of the panel. Thus, lightning discharges striking the trolley wires are prevented from reaching the distributors. The front of the panel is arranged for a telephone set by means of which motormen and linesmen may communicate with the supply station.

Fig. 456 illustrates a pillar suitable for the feeder pillars (Nos. 1, 5, 9) in the method of distribution shown in Fig. 451(*b*). The four upper switches control the trolley-wire sections, and the three lower switches control the feeder and distributors.

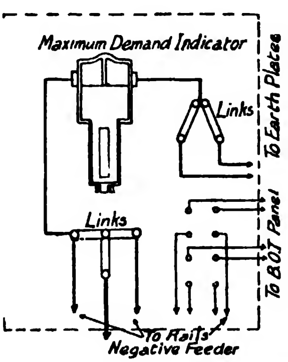


FIG. 457.—Arrangement of Negative Feeder Pillar.

The arrangement of a **negative feeder pillar** is indicated diagrammatically in Fig. 457. The negative feeder is connected to the track rails through a removable link, and the potential leads from the rails are connected to a set of terminals, which may be connected by suitable links to pilot wires running from the feeder pillar to the Board of Trade panel at the station. The station ends of the pilot wires are connected to recording voltmeters, which record the potential difference between the various points of the rails as required by statutory regulations. The pillar is also equipped with a maximum demand indicator, which is connected between the negative feeder and the earth plates. This maximum demand indicator enables a record to be obtained of the maximum current returning to the station via the earth plates.

(2) **Conduit tramways.** The arrangement of the standard feeder pillar adopted for the conduit lines of the London County Council tramways is shown in Fig. 458. The pillar contains two panels, each of which is fitted with four single-pole switches, the switches on the upper panel controlling, normally, the positive conductor rails. Each feeder terminates in a stud which may be connected to the switches on the respective panels by means of links at the back of the panels. In this manner several combinations between the feeders and the conductor rails can be made. Thus, in diagram No. 1, the feeders are connected to the left-hand switches; in diagram No. 2 they are connected to the right-hand switches; in diagram No. 3 the links are arranged so that

both of the adjacent sections of the track are fed from one feeder; and in diagram No. 4 the feeder is disconnected from the switches, and the right- and left-hand switches are connected together, so that one section of the conductor rails is fed from an adjacent section.

In the event of a fault occurring on the positive conductor rail of one section the fault must be transferred to the negative side of the system in order that the service may be continued. The feeders are, therefore,

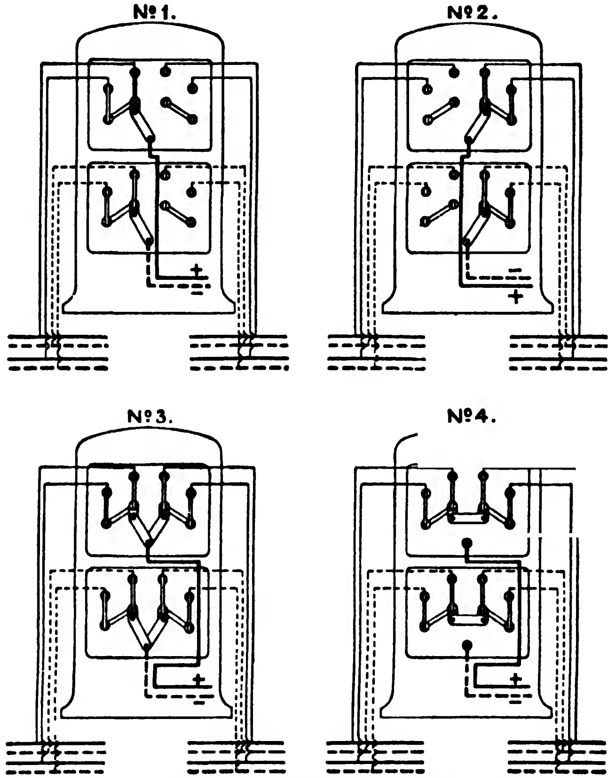


FIG. 458.—Arrangement of Switches in Feeder Pillars for Conduit Tramways.

arranged so that their polarity may be reversed when required, this operation being carried out by means of reversing switches on the substation switchboards.

FEEDING AND DISTRIBUTING SYSTEMS—DIRECT-CURRENT RAILWAYS

Location of substations. The design of the feeding and distributing system for urban and suburban railways, operating at an average voltage of 600 volts, is closely connected with the location of the substations. The distance between the substations is generally determined from considerations of the permissible variation of voltage at the trains, but it is advisable to consider also the location which will result in the minimum annual cost. In considering the voltage drop permissible in the conductor rails, the possibilities of delays due to signal stops should

be taken into account, as well as the maximum service which is likely to occur on the different sections. Moreover, when operating with the maximum service, the headway between consecutive trains will be smaller than that under normal service conditions, and, consequently, the checks at signals will probably be increased. For this reason, it is important to consider the position of the signals (especially the "stop" signals) and the "block" sections in arranging the positions of the feeding points.

The number of trains on a given section of the track is best determined from a **graphic time-table,** which is really a distance time chart for each individual train. By means of this chart the position of trains at important junctions—where two trains may have to use the same crossover—can readily be seen. As a first approximation in the preparation of such a chart from a completed time table, the distance-time curves of the trains may be assumed as straight lines. When the time table is not available, the chart must be prepared from the running curves of the trains. If the positions of stations and the "stop" signals are indicated on the chart, an approximate idea of the maximum load on the section can be obtained.

Method of determining distance between substations. The method to be employed is best illustrated by considering a specific case. For example, a service of 195-ton motor-coach trains has to be run over a double-track railway, on which the distance between the stations is 2560 ft., the schedule speed being 16 ml.p.h., and the duration of stop being 20 seconds. The track may be assumed to be straight and level. The train equipments are identical with those of the 195-ton six-coach train for which the speed-time curve and energy consumption were calculated in Chapter XIX.

The average voltage at the trains is to be 600 volts, and the converting machinery, to be used in the substations, is designed to give 600 volts at no load and 630 volts at full load. The distributing system consists of two (positive and negative) conductor rails weighing 100 lb. per yard.

The maximum service on the railway is 45 trains per hour in each direction,* which corresponds to a headway of (3600/45 =) 80 sec., and the voltage drop in the distributing system under these conditions is not to exceed 40 volts.

The distance between trains, on a given track, taking maximum current at the same instant is determined by constructing a series of distance-time and current-time curves for consecutive trains over a fairly long length (3 miles) of track. Such a set of curves, constructed from data in Chapter XIX, is given in Fig. 459. Hence, if a group of consecutive stations be designated A, B, C, D, etc., then at a given instant trains are starting simultaneously from stations A, D, G. (There is, however, a short time interval of 7 seconds between the successive starts.) Also, when a train is starting from station B, other trains are starting from stations E and F. Thus, the maximum currents may be considered to occur simultaneously at stations 7680 ft. apart.

* This is equivalent to the maximum service run over a portion of the District Railway, London. Obviously, this service is only possible in conjunction with automatic signalling.

The positions of the substations can now be fixed when the system of feeding has been decided. In order to simplify matters, we will assume that the conductor rails are continuous between the substations and that the feeding points are opposite the substations. A little consideration will show that if the substations are located at the passenger

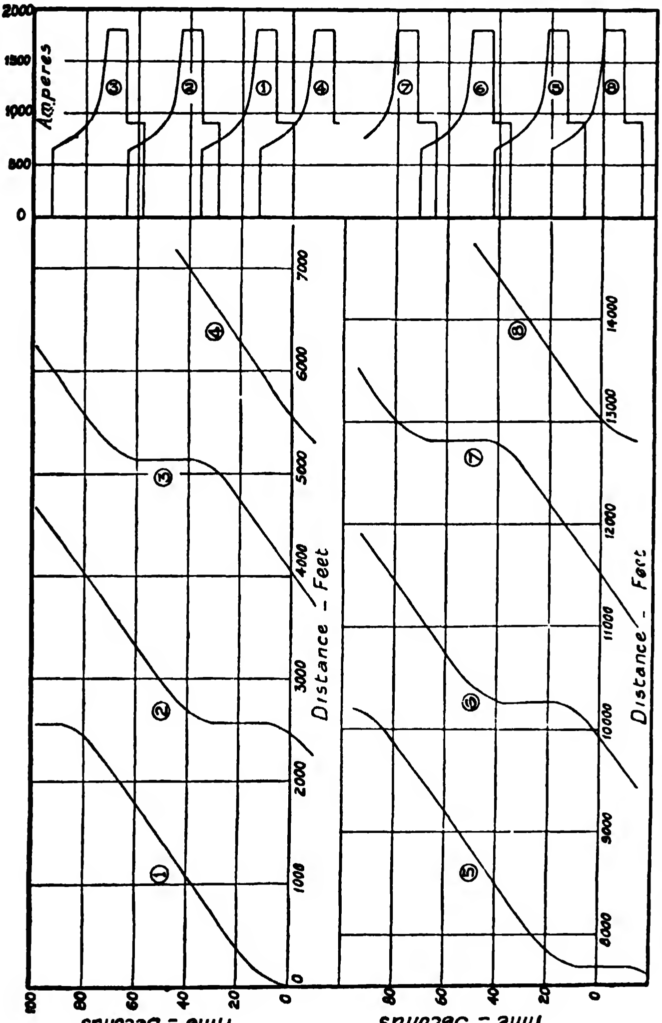


FIG. 459.—Method of Determining Distance between Trains taking Maximum Current.

stations A, D, G, etc., the maximum voltage drop will occur at the intermediate stations B, C, E, F, etc., and will equal 39·6 volts,* which

* When a train is starting from station B, two-thirds of the starting current will be supplied by substation A, and the remaining one-third by substation D, assuming equal voltages at the substations. Hence, as the resistance of the bonded conductor rails is 0·068 ohm per mile of track, the maximum voltage drop between a feeding point and a train is

$$\tfrac{2}{3} \times 1800 \times 0{\cdot}068 \times 2560/5280 = 39{\cdot}6 \text{ V}.$$

is equal to the specified value. Thus, with this arrangement of the feeders and conductor rails, the substations are 7680 ft. (nearly 1·5 miles) apart. Of course, if the conductor rails were also fed at intermediate points, the distance between the sul stations would be increased; but in this case very heavy feeders would be required, due to the relatively high conductivity of the conductor rail (which is equivalent to that of a feeder 1·33 sq. in. in cross-section). Moreover, the intermediate feeders would probably require boosters in order to make them thoroughly effective.

In this example the positions of the substations have been fixed from considerations of the permissible voltage variation at the trains. With systems on which the traffic consists of only a few trains per hour,

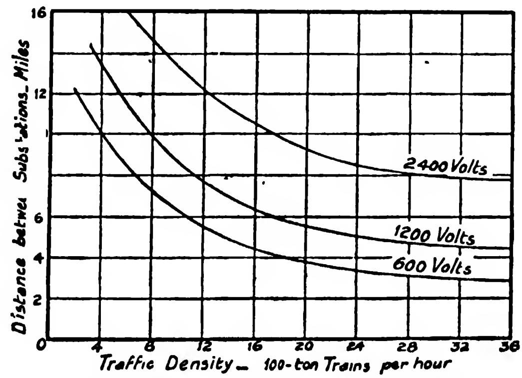


FIG. 460.—Most Economical Spacing of Substations for 100-ton Trains operating on Suburban Service.

it would be more economical to increase the distance between the substations and adopt a system of boosted feeders, as the increased load factor on the substations, together with the lower capital charges on the substations, will more than compensate for the cost of the boosters and feeders. In this connection, the curves of Fig. 460* are of interest. These curves show the relationship between the most economical spacing of the substations and the density of the traffic for a 36-mile double-track railway, having passenger stations 1 mile apart, on which is run a service of 100-ton trains at a schedule speed of 16 ml.p.h., with stops of 20 to 30 seconds duration. The effect of the operating voltage on the substation spacing is also shown.

Sectionalization of distributing system. With low-voltage direct-current railways, the lengths of the distributing sections are arranged to suit the requirements of the traffic, due consideration being given to the sectionalization at cross-overs and junctions.

The methods of sectionalizing the conductor rails are influenced by the method of operating adjacent substations (i.e. whether these substations are operated in parallel or separately): they also depend upon

* From a paper on the "Economics of Electric Railway Distribution," by Dr. H. F. Parshall. See *Minutes of the Proceedings of the Institution of Civil Engineers*, vol. 199, p. 47. The paper deals very fully with the spacing of substations for various conditions of traffic and various systems of distribution.

whether or not the "up" and "down" conductor rails of the same polarity are cross-bonded.

When substations operate in parallel a section insulator is inserted in the conductor rail opposite each substation, and the ends of the conductor rails are connected to double-throw (single-pole) switches, as shown in Fig. 461. When the switches in adjacent substations are

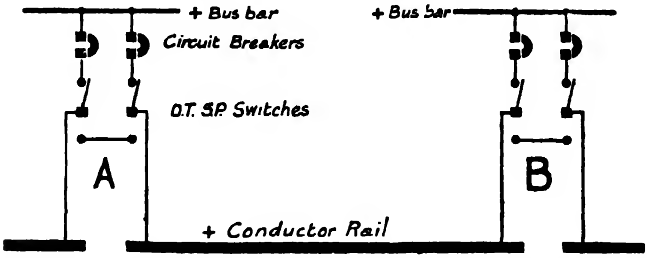


FIG. 461. Method of Feeding Conductor Rails with Substations operating in Parallel.

thrown into the upper contacts, the section of conductor rail between these substations is fed from each end, and the load on this section is therefore supplied from both of the substations. In the event of one substation being shut down, the switches are thrown into the lower

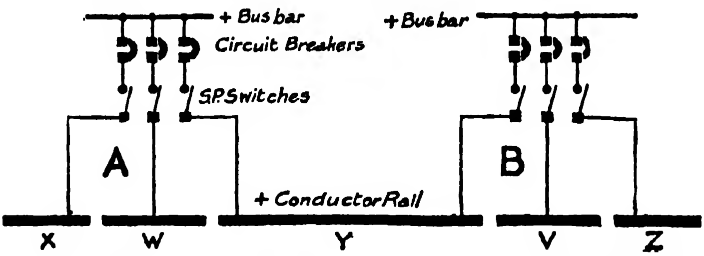


FIG. 462.—Method of Feeding Conductor Rails and "Train Sections" with Substations operating in Parallel.

contacts, thereby bridging the section insulators and transferring the load to the substations on either side.

This method of sectionalization, however, is not suitable when the traffic is operated with motor-coach trains having a power cable between the motor coaches, as if a fault occurred when the train was passing over the section insulator the circuit breakers on both sections would be tripped, thereby cutting off power from a considerable length of track. This objection can be removed by inserting a separate section (the length of which is slightly greater than the extreme distance between the front and rear collector shoes) between the main sections, and feeding this section separately. Thus, in Fig. 462, two substations are represented at A and B. Substation A supplies the sections X, W, Y, while substation B supplies the sections Y, V, Z. Of these sections, X, Y, Z represent the main sections of the conductor rails, while W, V represent the special short sections (called "**train sections**") opposite each substation. It is apparent that an overload on a main section only, or a

main section and a train section together, will only shut down one main section.

In those cases where the substations do not operate in parallel provision must be made for bridging the sections supplied from neighbouring substations, so that, in an emergency, these sections can be supplied from one substation. The switches for this purpose are generally located in section pillars adjoining the track.

Another feature in which a system supplied from separate substations differs from one in which the substations operate in parallel is the **cross-bonding of the conductor rails** of the same polarity. This cross-bonding is usually carried out by switches located in pillars adjacent to signal cabins, so that the switches may be operated by the signalman on instructions from the responsible department. Under normal conditions of operation the switches are closed, and the "up" and "down"

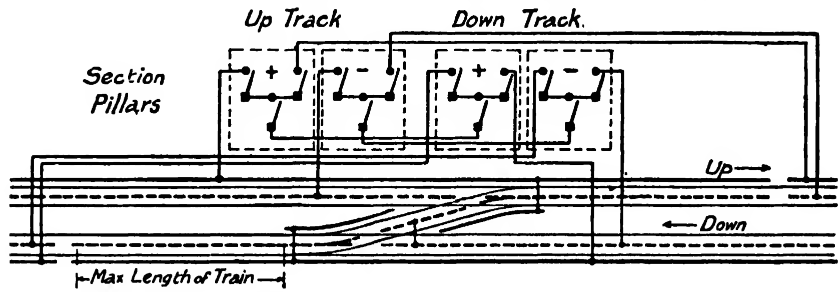


FIG. 463.—Arrangement of Conductor Rails and Sectionalizing Switches at a Cross-over.

conductor rails of the same polarity are connected together at a number of points, so that the full conductivity of the conductor rails is available.

The method of sectionalizing and feeding the conductor rails at **station cross-overs** is important, as provision must be made, in the case of a breakdown, for single-line working or for shuttle working. A diagram showing the switches and conductor-rail sections to fulfil these requirements is shown in Fig. 463.

FEEDING AND DISTRIBUTING SYSTEMS—ALTERNATING-CURRENT RAILWAYS

Calculation of the voltage drop. This calculation, for a feeder or distributor, involves the consideration of the effects of resistance, self-induction, mutual-induction, and power factor.

The effect of power factor on voltage drop is shown, for the case of a feeder, in the vector diagram of Fig. 464, in which OI represents the current, OV the voltage at the load or receiving end of the feeder, and OE the voltage at the generating station. OE is compounded from OV and VE, which represents the voltage drop due to the impedance of the feeder. The impedance voltage, VE, may be resolved into a component, Va, in phase with the current, and a component, aE, in quadrature (leading) with the current. These components are numerically equal to IR and $2\pi fLI$ respectively, where I denotes the current, f the frequency, and R, L the resistance and inductance, respectively, of the feeder.

The actual voltage drop (v) in the feeder (i.e. the arithmetic difference between the voltages at the two ends) is given with sufficient exactness by VA, since, in practice, a is a very small angle. Hence, from the geometry of Fig. 464,

$$v = I(R \cos \phi + 2\pi f L \sin \phi) \quad . \quad . \quad . \quad . \quad . \quad (59)$$

The inductance can be calculated from the dimensions and spacing of the conductors forming the circuit.* With two similar parallel wires of radius r, spaced at a distance D apart, the inductance (in henries) per route mile is given approximately by $L = 0{\cdot}00161(0{\cdot}92 \log D/r + 0{\cdot}1\mu)$ . . (60) where μ is the permeability of the conductor ($\mu = 1$ for all non-magnetic materials). In this equation the first term is due to the magnetic field external to the conductors, and the second term ($0{\cdot}1\mu$) is due to the magnetic field inside the conductors.

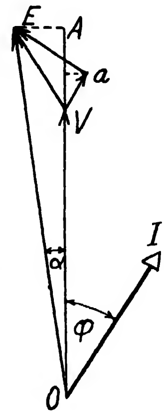


FIG. 464.
Vector Diagram for Feeder.

With a traction circuit, however, the trolley wire and rails differ considerably in dimensions and magnetic properties; and therefore the inductance of such a circuit must be obtained by calculating separately the inductance of each part. Now the self-inductance of a *single* straight isolated wire is given (in henries) by $L_s = 2l[2{\cdot}3 \log(2l/r) - 1 + \frac{1}{4}\mu] \times 10^{-9}$ . . . (61) in which l and r denote respectively the length and radius of the wire in centimetres.

But if this wire forms part of a circuit, the mutual inductance of the return conductor must be considered in calculating the inductance of the outgoing wire. For example, if the return portion of the circuit consists of two conductors parallel to the outgoing conductor and I, I_1, I_2 denote the currents in the conductors, I being the current in the outgoing conductor, then, since $I = (I_1 + I_2)$, the inductance of a length l (cm.) of the *outgoing* conductor is given by

$$\begin{aligned} L_o = 2l & \left\{\left(2{\cdot}3 \log \frac{2l}{r} - 1 + \frac{1}{4}\mu\right) - \left(2{\cdot}3 \log \frac{2l}{D_1} - 1\right)\frac{I_1}{I} \right. \\ & \left. - \left(2{\cdot}3 \log \frac{2l}{D_2} - 1\right)\frac{I_2}{I}\right\} \qquad 10^{-} \\ & = 2l(\tfrac{1}{4}\mu + 2{\cdot}3 \log[(D_1^{I_1/I} \times D_2^{I_2/I})/r]) \times 10^{-9} \qquad (62) \end{aligned}$$

where r is the radius of the outgoing conductor, and D_1, D_2, are the distances between the outgoing and each return conductor.

The inductance of a length l (cm.) of one of the *return* conductors (say, No. 1) is given by

$$\begin{aligned} L_1 = 2l & \left[\left(2{\cdot}3 \log \frac{2l}{r_1} - 1 + \frac{1}{4}\mu\right) - \frac{I}{I_1}\left(2{\cdot}3 \log \frac{2l}{D_1} - 1\right) \right. \\ & \left. + \frac{I_2}{I_1}\left(2{\cdot}3 \log \frac{2l}{D_3} - 1\right)\right] \times 10^{-9} \\ & = 2l[\tfrac{1}{4}\mu_1 + 2{\cdot}3 \log(D_1^{I/I_1}/r_1 D_3^{I_2/I_1})] \times 10^{-9} \end{aligned}$$

* See the author's *Theory and Practice of Alternating Currents*, p. 37.

where r_1 is the radius of this conductor, μ_1 its permeability, and D_3 the distance between the two return conductors.

Similarly, the inductance of a length l (cm.) of the other return conductor (No. 2) is given by

$$L_2 = 2l[\tfrac{1}{4}\mu_2 + 2{\cdot}3 \log (D_2^{I/I_2}/r_2 D_3^{I_1/I_2})] \times 10^{-9}$$

where r_2 is the radius of this conductor and μ_2 its permeability.

Example. A single-track, standard gauge, single-phase railway is laid with 80-lb. track rails, which are cross-bonded, the distance between the centres of the rails being 4·9 ft. The copper trolley wire is 0·5 in. in diameter, and

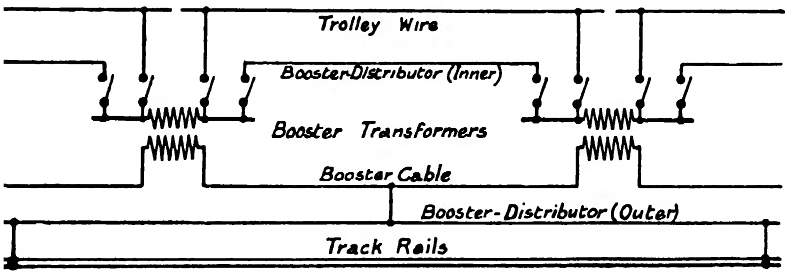


FIG. 465.- Method of Connecting Booster Transformers for Neutralizing Voltage Drop in Rails.

is suspended centrally 17 ft. above the rails. Calculate the inductance per mile.

On account of the symmetrical arrangement of the trolley wire and rails, the inductive effect of the latter upon the former will be the same as if the return current passed through a single conductor [$\sqrt{(17^2 + 2{\cdot}45^2)} =$] 17·17 ft. below the trolley wire.

The inductance of 1 mile of the trolley wire is

$$2 \times 0{\cdot}00161\ [0{\cdot}25 + 2{\cdot}3 \log (17{\cdot}17 \times 12/0{\cdot}25)] = 0{\cdot}00223 \text{ henries.}$$

To calculate the inductance of the rail return the equivalent radius and the permeability must be known.

The former may be considered equal to (perimeter of rail/$2\tfrac{1}{2}$): the latter depends upon the chemical composition of the rail, and on the current passing through it. In the present case we will assume the perimeter of the rail as 18·8 in., and the permeability as 40. Hence the inductance in henries per mile of the rail return is

$$\tfrac{1}{2} \times 2 \times 0{\cdot}00161[\tfrac{1}{4} \times 40 + 2{\cdot}3 \log 17{\cdot}17^2/(18{\cdot}8 \times 4{\cdot}9/2\pi \times 12)]$$

NOTE. The index 2 in the logarithmic term is obtained from the ratio of the current in the trolley wire to the current in one rail, each rail being assumed to carry one-half of the current in the trolley wire.

Impedance of rail return. In calculating the impedance of the rail return due consideration must be given to the fact that the effective resistance of the rail when carrying alternating current is higher than the resistance when carrying direct current owing to the "skin effect" (i.e. the concentration of the current to the outer portion of the rail), the magnitude of which depends upon the frequency and the magnetic properties of the conductor. In the case of conductors consisting of

magnetic materials, the current is confined to a thin surface layer of the conductor, the thickness (δ) of which is given by

$$\delta = \sqrt{(\rho/2\pi\mu\omega)}$$

where ρ denotes the specific resistance of the material, μ the permeability and $\omega = 2\pi \times$ frequency.

From a number of tests* on track rails carrying alternating currents, the thickness of the surface layer has been computed at from 3 to 4

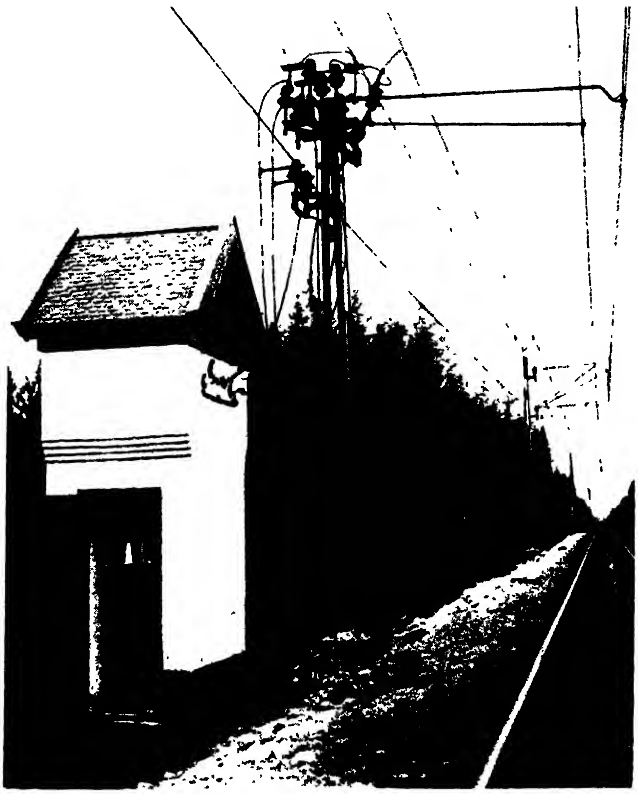


Fig. 466.—Booster Transformer and Sectionalizing Switch on Swedish State Railways (A.S.E.A.).

millimetres for the frequencies and currents appropriate to alternating-current railways. The equivalent resistance of the track rails when carrying alternating currents may therefore be calculated from δ, ρ, and the perimeter (p) of the rail.

Assuming $\delta = 3$ mm. and $\rho = 8 \times 10^{-6}$ ohms per inch cube, the equivalent resistance (R) per foot of rail is given by $R = 813/p \times 10^{-6}$ ohms, p being the perimeter of the rail in inches.

Hence the equivalent resistance of 1 mile of cross-bonded single track laid with 80 lb. rails is ($1{\cdot}2 \times \frac{1}{2} \times 5280 \times 10^{-6} \times 813/18{\cdot}8 =$) 0·15 ohm. [Note.—The factor 1·2 is to allow for the resistances of the joints.]

* *Electrician*, vol. 56, p. 757.

Therefore, in the above example, if the frequency is $16\frac{2}{3}$ cycles per second, the impedance per mile of track return

$$\sqrt{[0{\cdot}15^2 + (2\pi \times 16\tfrac{2}{3} \times 0{\cdot}0025)^2]} = 0{\cdot}3 \text{ ohm}.$$

If the return current is 120 amperes, the voltage drop per mile of track return = $120 \times 0{\cdot}3 = 36$ volts.

Thus the use of the track rails solely as return conductors in alternating-current systems involves large potential differences along the track which may cause serious interference with telegraphic and other apparatus employing an earth return.

Methods of relieving rails of return current. If the potential difference between any two points of the rail return is to be maintained at a low value the rails must be relieved of a large portion of the return current,

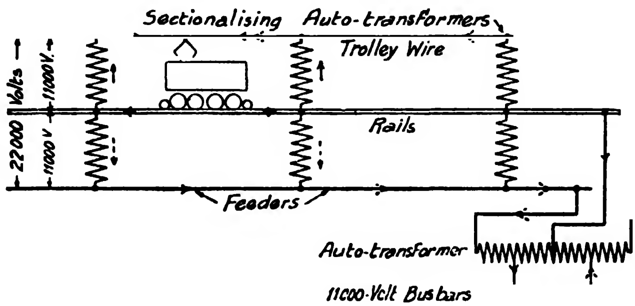


FIG. 467.—Method of Connecting Overhead Feeders and Trolley-wire to Minimize Interference Effects on Neighbouring Circuits.

which may be effected by the use of a distributor cable in conjunction with booster transformers. Such a system is shown diagrammatically in Fig. 465, in which the sections of the trolley wire are supplied from the inner conductor of a concentric distributor, which is divided up into the same number of sections as the trolley wire, the sections being connected through the primary windings of the booster transformers (of 1 : 1 ratio). Thus the primary windings of the booster transformers are all connected in series. The secondary windings of these transformers are also connected in series by a single insulated cable (called the "booster" cable), which is connected at certain points to the (earthed) outer conductor of the concentric distributor, this conductor being also connected to the rails at frequent intervals.

Hence, since the booster transformers have a ratio of unity and the secondary winding is connected to a closed circuit, the primary and secondary currents will be practically equal (the difference between these currents being equal to the magnetizing current of the transformers), and consequently the cable connecting the secondary windings of the transformers must carry a current approximately equal to that in the inner conductor of the concentric distributing cable. Therefore practically all the return current will be drawn from the rails into the booster cable.

The E.M.F. in the secondary winding of the booster transformers (which neutralizes the impedance voltage drop in the secondary circuit)

is obtained from the primary winding, so that the voltage drop in the return conductor is transferred to the outgoing conductor (i.e. the inner conductor of the concentric distributing cable).

Fig. 466 shows a booster transformer and section switch installed on the 15,000-volt lines of the Swedish State Railways. The booster transformers are located at intervals of about 2·8 kM. (1·75 ml.). In this case,

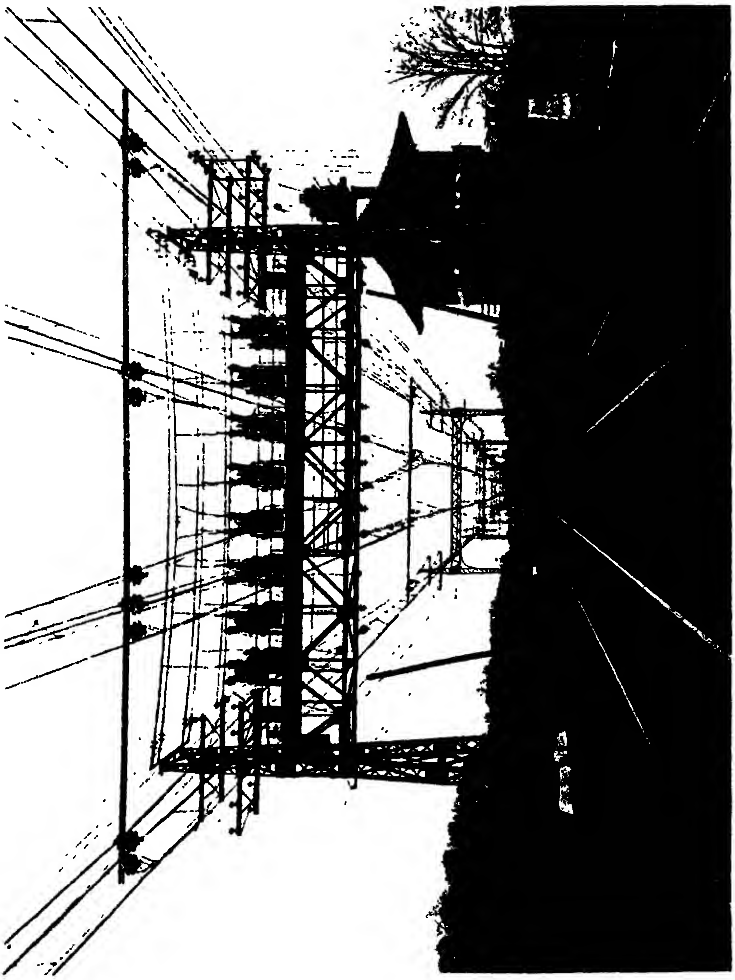


Fig. 468.—Sectionalising Gantry and Outdoor Auto-transformer Sub-station (N.Y., N.H., and H.R.R.).

however, the booster cable is a single bare conductor supported, by insulators, from the poles at approximately the same height as the trolley wires.

Interference effects on telegraph and telephone circuits. Single-phase currents in trolley wires produce electromagnetic and electrostatic disturbances in parallel telegraph and telephone circuits. In some cases the disturbances have been so severe that the telephone circuits have had to

be run underground, and in other cases various devices have had to be adopted to neutralize the inductive effects in the auxiliary circuits..

The electromagnetic inductive effects can be minimized by employing booster transformers and a return conductor arranged parallel to the trolley wires, as in Figs. 428, 466.

Alternatively, the scheme shown diagrammatically in Fig. 467 may be employed. In this case the feeders are supplied at double the voltage of the trolley wire, the latter being fed from the former through auto-transformers. The centre point of the winding of each auto-transformer is connected to the rails. Hence the currents in the portions of the trolley wire between adjacent transformers are in opposite directions—as shown in Fig. 467—so that the resultant inductive effect on a neighbouring circuit is practically zero. This arrangement of the feeders and trolley wires also minimizes the electrostatic effects on neighbouring circuits.

On the New Haven electrified lines the auto-transformers are of the outdoor type, and are placed alongside the track at intervals of from 2 to 8 miles, according to the density of the traffic. The sectionalizing switches—which also form overload circuit-breakers—are of the electrically-operated oil-break type, and are placed on the top of the sectionalizing gantries, the switches being controlled from an adjacent signal cabin. A typical sectionalizing gantry, showing the switches and the outdoor auto-transformer substation, is shown in Fig. 468.

CHAPTER XXVII

SUBSTATIONS

THE supply of energy to the distribution systems of extensive railways is best effected from substations, as, even with single-phase electrifications, the distribution voltage is too low for the transmission of large amounts of energy over long distances. The type of substation plant employed will depend upon the nature of the primary supply and the system of electrification. Thus if the railway purchases energy from a general extra-high voltage three-phase network (or "grid"), rotating converting machinery will be necessary for both single-phase and direct-current electrifications, and may also be required for three-phase electrifications if the locomotive equipments are built for low frequency. On the other hand, if the generating stations are designed solely for supplying the railway load, the frequency of the generators can be chosen for this load, so that, for alternating-current electrifications, no rotating machinery will be necessary in the substations.

I. SUBSTATIONS FOR SINGLE-PHASE RAILWAYS

In many European single-phase railways the primary supply system is designed solely for the railway load; the generators being single-phase low frequency ($16\frac{2}{3}$ cycles) machines, wound for the distribution voltage (15,000 volts), in order that tracks near the generating station may be supplied direct. The substations are supplied by high-voltage (66–132 kV.) transmission lines, which are fed through transformers at the generating station.

With the object of saving the cost of expensive buildings for housing the transformers and switchgear, modern transformer substations are of the outdoor type. The transformers and extra-high voltage switchgear are installed out of doors, the switches being power operated and remote controlled from a central control room containing desk-type switchboards, on which are mounted the control switches, measuring instruments, and remote indicating devices. The high-voltage lines entering the substation, and also the feeders for the traction distributing system are dead ended to steel structures; and the connections to the switches, transformers, etc., are made by bare copper tubes or cables.

Figs. 469–471 show typical substations of the **Swiss Federal Railways.** The transformers and switches are mounted above ground level on concrete blocks; the layout being such as to facilitate the removal and replacement of any piece of apparatus. When sufficient ground area is available the apparatus is so arranged that the interconnections are self-supporting, thus eliminating a large number of steel structures and insulators which would otherwise be necessary. This layout, however, requires more ground area for a given number of transformers, switches, etc., than that (Fig. 469) in which the interconnections are suspended from insulators attached to lattice gantries.

These outdoor substations have given very satisfactory service in Switzerland under all conditions of weather, and the switchgear has been

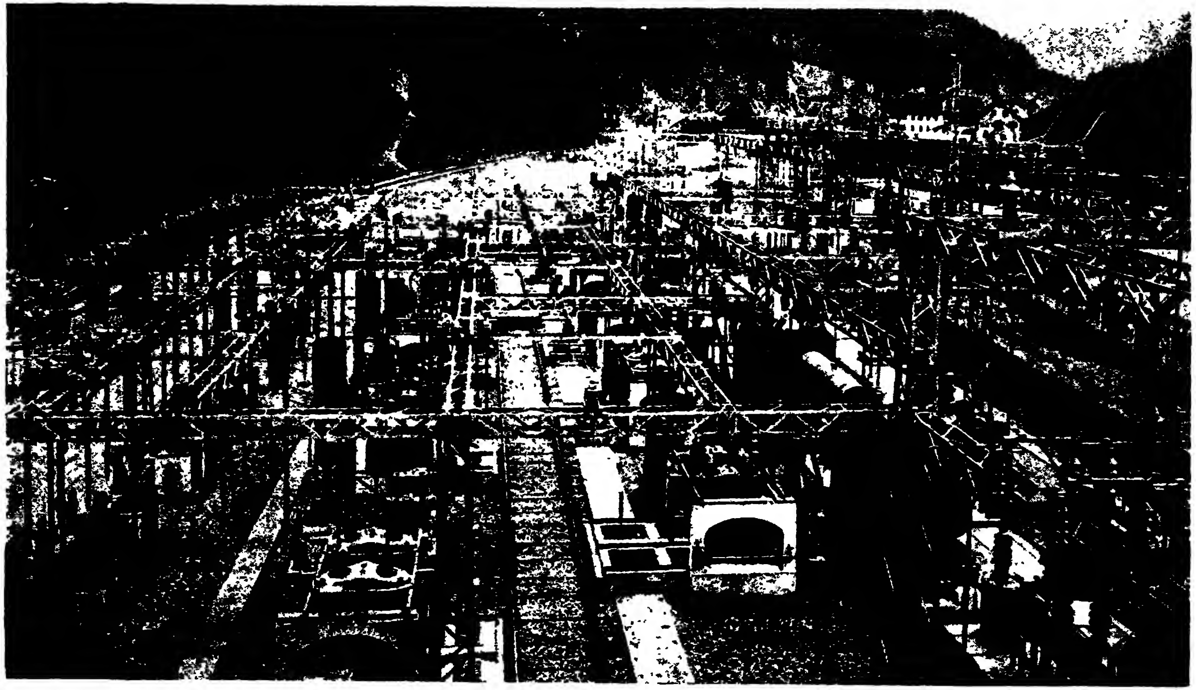


FIG. 469.—Outdoor Substation (60/15 kV.) of Swiss Federal Railways.
[NOTE.—The 60 kV. switchgear and bus-bars are on the right; the 15 kV. switchgear bus-bars and out-going feeders are on the left.]
[Oerlikon.]

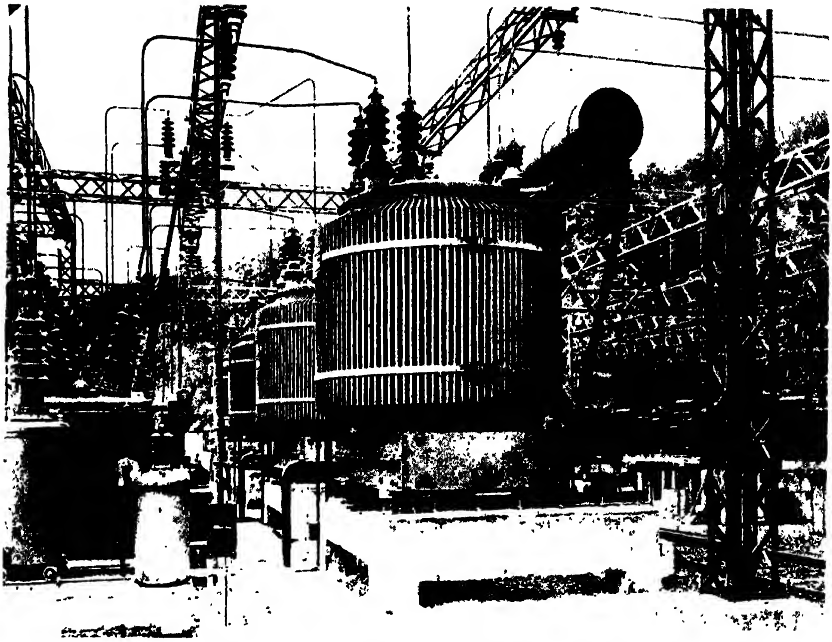


Fig. 470.—Transformers and 60 kV. Switchgear (left) in Outdoor Substation of Swiss Federal Railways. [Oerlikon.]

Fig. 471.—3000 kVA. Transformers in Outdoor Substation of Swiss Federal Railways. [Brown-Boveri.]

unaffected by heavy snowfalls (the substations continuing in service with the 15 kV. switchgear insulators covered in snow).

The Stockholm-Gothenburg main lines of the **Swedish State Railways,** however, receive energy from a 50-cycle, three-phase, 132-kV. network, and accordingly the substations have had to be equipped with converting plant. The substations are situated at railway stations about 80–100 kM. (50–62 ml.) apart, and are equipped with transformers and motor-generators. The three-phase step-down transformers and the 132 kV. switchgear are of the outdoor type ; but the single-phase step-up transformers, the (16 kV.) switchgear for the traction circuits, and the switchgear for controlling the motor-generators, are of the indoor type. The motor-generators (of which there are twelve distributed between five substations) each consist of a three-phase 12-pole synchronous motor (3200 kVA., 6,300 volts), a single-phase 4-pole alternator (2400 kVA., 3000 volts), and exciters. The motor is arranged for self-starting from an auto-transformer, and the alternator of each set is directly connected to a step-up transformer (3000/16,000 volts) from which the traction circuits are supplied. This transformer protects the alternator windings from the effects of short-circuits and lightning discharges on the trolley wires.

II. Substations for Direct-Current Tramways and Railways

These substations must be equipped with either rotating converting machinery (e.g. rotary converters, motor-converters or motor-generators) or static (mercury-arc) rectifiers. In cases where the supply frequency, distribution voltage, physical conditions of location, and special operating conditions (e.g. regenerative braking) do not restrict the choice of plant, the type of plant to be installed is obviously that which will give the lowest annual cost (which is made up of (*a*) the capital charges on the plant and buildings ; (*b*) the fixed "running charges, e.g. the costs of attendance and maintenance ; and (*c*) the variable "running" charges, i.e. the costs of the energy losses in conversion, repairs, and overhauls). Of the rotating types of substation plant the rotary converter has the lowest annual cost, and, therefore, for low-voltage traction systems the choice of plant will rest between the rotary converter and the rectifier. With high-voltage traction systems, however, the choice will rest usually between the rectifier and the motor-generator. But if regenerative braking is to be employed, the complete equipment of the substations with rectifiers is inadmissible.

In view of the importance of rotary converters, rectifiers and motor-generators in the equipment of traction substations, we shall consider briefly their characteristics and operating features.

Rotary Converters

General. A rotary converter consists of a stationary field magnet (Fig. 472) and a rotating armature (Fig. 473) having a single winding which is connected to both a commutator and a set of slip rings. Energy in the alternating-current form is supplied to the slip rings and is converted, by the synchronous rotation of the armature, into the direct-current form. For a given flux distribution in the air gap a fixed ratio exists between the voltages at slip rings and commutator, the slip-ring voltage being lower than the commutator voltage.

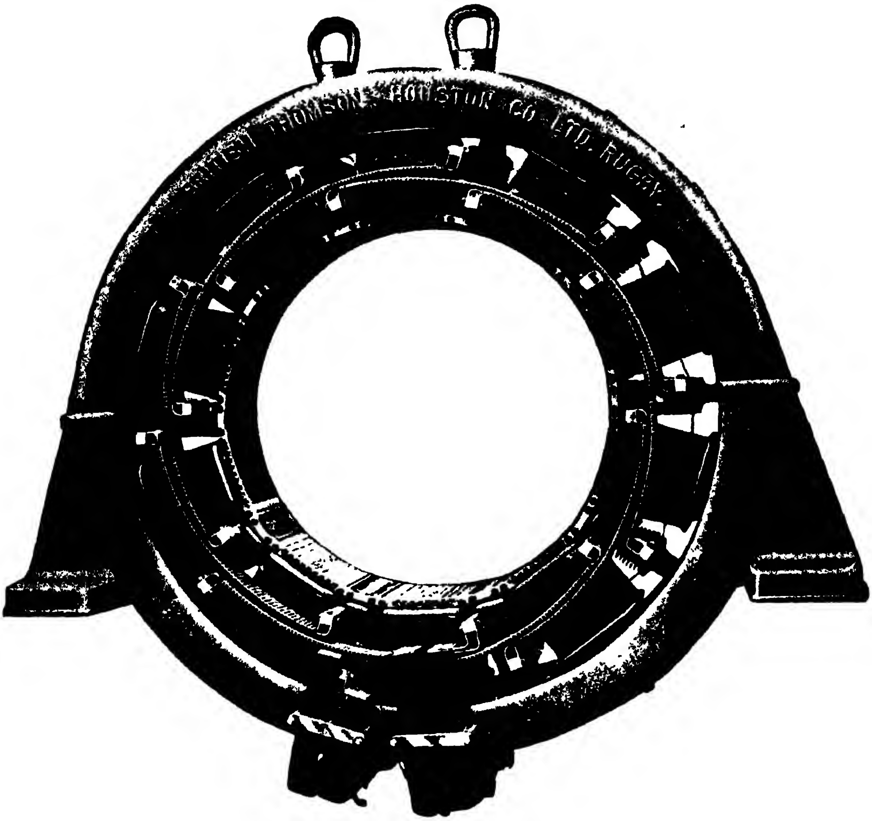


Fig. 472.—Magnet Frame of Rotary Converter. (B.T.-H. Co.)

[Note.—The main poles shoes are laminated and are fitted with a damping winding (consisting of short-circuited copper bars) for the purpose of damping oscillations in speed due to irregularities in the supply frequency.]

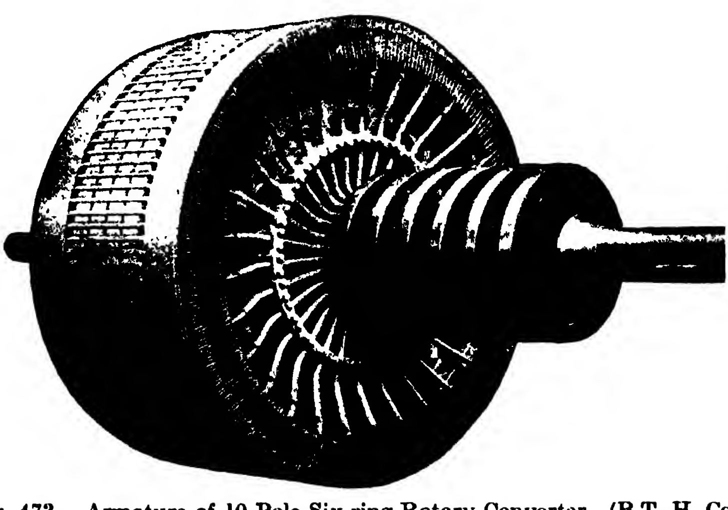


Fig. 473.—Armature of 10-Pole Six-ring Rotary Converter. (B.T.-H. Co.)

When supplied with alternating current the rotary converter is essentially a synchronous machine; the speed being given by $n_{r.p.s.} = f/\frac{1}{2}p$, where f = frequency, p = number of poles. It is sensitive to irregularities in the supply frequency—such irregularities producing surging or "hunting"—and it may drop out of synchronism when subjected to abnormally heavy overloads or to large and sudden reductions in the supply voltage. Reversible operation (i.e. direct to alternating) is possible, but precautions must be taken to avoid dangerous operating conditions (i.e. excessive speeds), as the speed is now dependent upon the resultant excitation. Lagging currents in the armature produce a demagnetizing effect on the field magnets and would,

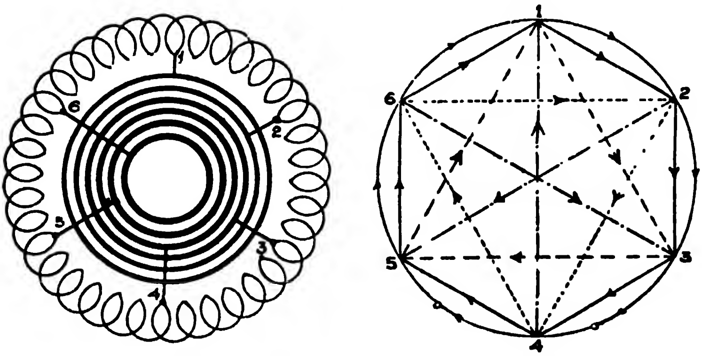


FIG. 474.—Circuit and Vector Diagrams of E.M.F.'s. for Armature of Six-ring, Two-pole, Rotary Converter.

[NOTE.—Circle represents E.M.F.'s. in armature winding; inscribed hexagon, triangles and stai represent E.M.F.'s. between 60°, 120°, and diametrical tappings respectively.]

therefore, cause an increase of speed if the exciting current were maintained constant.

Compared with other types of commutating machinery the rotary converter has a very large overload capacity, which is a valuable asset for traction service.

E.M.F. ratio. With sinusoidal flux distribution and sinusoidal supply E.M.F. the ratio of slip ring to commutator voltages (E_s, E_c, respectively) at no load is given by

$$E_s/E_c = 0{\cdot}707 \sin(\pi/m)^* \qquad (63)$$

where m denotes the number of slip rings.

Hence with three rings $E_s/E_c = 0{\cdot}707 \sin \frac{1}{3}\pi = 0{\cdot}612$. With six rings E_s/E_c has the values $0{\cdot}354 (= 0{\cdot}707 \sin \frac{1}{6}\pi)$; $0{\cdot}707 (= 0{\cdot}707 \sin \frac{1}{2}\pi)$; $0{\cdot}612$ $(= 0{\cdot}707 \sin \frac{1}{3}\pi)$; according to whether the alternating E.M.F. (E_s) is taken between adjacent tappings, diametrical tappings, or tappings 120° apart. These conditions are represented in Fig. 474.

Voltage control. In cases where the bus-bar voltage is required to increase automatically with increase of load, and the full-load voltage is within about 15 per cent of the no-load voltage, the voltage variation is obtained by

* Thus, in a two-pole machine, if the armature has $2N$ turns, of full-pitch and uniformly distributed, the number of turns between adjacent tappings—which embrace an angle $2\pi/m$—is $2N/m$, and the number of turns between the brushes on the commutator is N. Hence if Φ is the flux per pole and f is the frequency

$$E_s = 4(\pi 2/\sqrt{2})10^{-8}[\sin \tfrac{1}{2}(2\pi/m)/\tfrac{1}{2}(2\pi/m)]\Phi f\, 2N/m = (4/\sqrt{2})10^{-8}\, \Phi f N \sin(\pi/m)$$

$$E_c = 4\Phi f N \times 10^{-8}$$

Whence $E_s/E_c = (1/\sqrt{2}) \sin(\pi/m)$.

means of a compound winding on the rotary converter in conjunction with inductive reactance in the secondary circuit of the transformer. The object of the compound winding is to produce automatically a change of power factor with change of load, and so cause a corresponding change in the phase of the voltage drop in the circuit, thereby resulting in a change of slip-ring voltage. Thus in the vector diagram, Fig. 475, *OE* represents the E.M.F. (assumed to be constant) induced in the secondary winding of the transformer, *OI* the current in this winding, *OZ* the voltage drop due to the impedance of the circuit, and *OV* the voltage at the slip rings.

In cases where large changes of power factor are inadmissible, or where the voltage and power factor are to be regulated independently, the voltage variation is best obtained by means of an induction regulator connected between the transformer terminals and the slip rings. Alternatively, a synchronous booster or divided main poles (in which the excitation of each portion of the pole is independently adjustable) may be employed. Divided, or split pole, machines, however, are only suitable for low-frequency circuits.

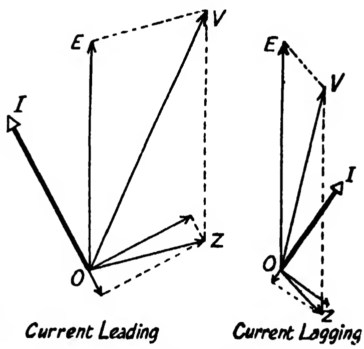


FIG. 475.—Vector Diagram.

When a machine is required to operate at two different voltages—e.g. for supplying either a traction circuit (550 volts) or a three-wire lighting circuit (460 volts)—the simplest and cheapest method is to provide suitable tappings on the primary winding of the transformer together with a tap-changing switch.

Armature heating and I^2R loss. The armature current is the resultant of the input (alternating) and output (direct) currents, but is not uniformly distributed throughout the armature winding, the coils near the tappings carrying larger currents than those midway between the tappings.* The non-uniformity in the distribution of the current, as well as the mean value of the resultant current, both decrease as the number of phases increases, assuming other conditions to remain constant. The mean value of the resultant current, however, increases rapidly as the power factor departs from unity.

For the same output from a given armature the ratio of I^2R losses for rotary converter and generator operation are—

0·56	for three slip rings, unity power factor.		100% efficiency.	
0·84	,,	,,	0·9	.. 100%
0·27	for six slip rings, unity power factor,		100% efficiency.	
0·366	,,	,,	0·95	,, 100%
0·47	,,	,,	0·9	.. 100%
0·51	,,	,,	0·9	,, 95%

Hence, for equal heating under given conditions, the permissible output of a rotary converter is much greater as a six-phase machine than as a three-phase machine, and therefore all except the smallest machines are built for six-phase operation (i.e. with six slip rings).

* The r.m.s. value of the resultant current in a conductor $\theta°$ from the mid-point of a pair of tappings is

$$I = \frac{I_c}{a}\sqrt{\left(1 + \frac{8}{[\eta\cos\varphi \times m\sin(\pi/m)]^2} - \frac{16\cos\theta}{m\pi\sin(\pi/m)}\right)} \quad . \quad . \quad . \quad (64)$$

where I_c is the current output from the commutator, a the number of circuits in the armature winding, η the efficiency, $\cos\varphi$ the power factor, m the number of slip rings.

Efficiency. In consequence of the relatively small armature I^2R losses compared with the output, the efficiency of rotary converters is higher than that of other commutating machines. Representative values are—

(1) 1500 kW., 6-pole, 25 frequency, 600-volt rotary converter (with transformer)

Percentage of full load . .	50	75	100	125	150
Percentage efficiency . .	94·6	95·3	95·3	95·1	94·7

(2) 1500 kW., 12-pole, 50 frequency, 600-volt rotary converter (with transformer)

Percentage of full load . .	50	75	100	125	150
Percentage efficiency . .	93·1	94·4	94·7	94·7	94·5

Energy supply to armature. The vector diagram of Fig. 474 shows that the armature of a six-ring machine may be supplied with energy in three ways, viz. (1) from a *six-phase system* having line voltages equal to 0·354 E_c ; (2) from *three single-phase systems* having mutual phase differences of 120° and line voltages equal to 0·707E_c ; (3) from *two three-phase* systems having a phase difference of 180° and line voltages equal to 0·612E_c. These systems may all be obtained from a three-phase supply by providing suitable windings on the transformer.* In practice, only methods (2) and (3)—called the "diametrical" and "double-delta" methods respectively—are employed, the connections being shown in Fig. 476. The diametrical connection is

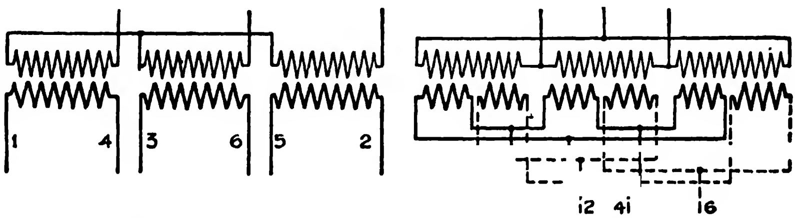


FIG. 476.—Methods of Connecting Transformers for Supplying Six-phase Rotary Converter from Three-phase Supply System. [The numbers 1–6 refer to the Slip Rings (Fig. 474).]

usually preferred on account of the lower costs of the transformer and connecting cables (which are due to (1) the single secondary windings ; (2) the higher secondary voltages ; (3) the absence of interconnections between the secondary windings).

Starting. Rotary converters are usually started from the alternating-current side so as to eliminate synchronizing operations. The machine may be started, at low voltage, as an induction motor, or, alternatively, the initial starting may be effected by a separate (induction) motor.†

Limitations. (1) The **maximum commutator voltage** is limited by (*a*) the permissible average voltage (E_{av}) between commutation segments, (*b*) the number of segments per pole. The latter may be expressed in terms of the segment pitch (τ_c), peripheral speed of commutator (v_c), number of poles (p) and frequency (f). Thus, if v_c is expressed in feet per minute and τ_c in inches, we have

$$E_c = E_{av}v_c/(10f\tau_c) \quad . \quad . \quad . \quad . \quad . \quad . \quad (65)$$

Taking limiting values as—$E_{av} = 18$, $v_c = 8000$ ft. per min., $\tau_c = 0·18$ in., then for 50 frequency,

$$E_c = 18 \times 8000/(10 \times 50 \times 0·18) = 1600 \text{ volts.}$$

* The theory of the methods is given in the author's *Theory and Practice of Alternating Currents*, pp. 212–219.

† Diagrams of connections and details of the starting procedure are given in the author's *Power Wiring Diagrams*, pp. 146–151.

Hence, although 1500-volt, 50-cycle rotary converters are practicable, they are essentially high-speed machines having few poles and a high value for the mean voltage per commutator segment.

(2) The permissible **output per pole** at the continuous rating is easily deduced from first principles, and is given by

$$E_c I_c/p = E_{av} v_c Q/[(10fD_c/D)\sqrt{\psi}] \quad . \quad . \quad . \quad (66)$$

where E_c, E_{av}, v_c, f have the same significance as in the preceding equation; I_c is the direct-current output at continuous rating, Q the specific electric loading (i.e. ampere-turns per inch of armature periphery); ψ the ratio of armature I^2R losses as rotary converter and direct-current generator (p. 645); D_c/D the ratio of commutator and armature diameters; p the number of poles.

Taking $E_{av} = 18$, $v_c = 8000$, $Q = 500$, $f = 50$, $\psi = 0{\cdot}4$, $D_c/D = 0{\cdot}9$, we have

$$E_c I_c/p = 253 \times 10^3 \text{ watts.}$$

(3) The **commutation** at sudden overloads and short circuits is an important feature in rotary converters for traction service. To secure freedom from flash-over under these conditions, high-reluctance commutating poles of special design are necessary, which, with 1500-volt machines, may be supplemented by devices (viz., an axial air blast in conjunction, in some cases, with magnetic blow-outs on the brush holders) for removing as rapidly as possible from the commutator any conducting vapours formed during sparking.

Motor-Generators and Motor-Converters

Motor generators are preferred to other types of rotating converting plant for the supply of direct current at pressures above 1500 volts. For distribution pressures of 3000 volts 1500-volt generators are employed, two generators being connected in series and driven by a common synchronous motor. Such generators are always separately excited (from a low-voltage exciter) and are provided with compensating (pole face) windings for neutralizing armature reaction. In many cases an air blast and magnetic blow-outs on the brush holders are also provided to prevent flashing-over at the commutator when the machines are subjected to external short circuits.

Motor-generator sets of this type have given very satisfactory service on the 3000-volt lines of the Chicago, Milwaukee and St. Paul Railroad and the South African Railways,* the twelve substations of the latter being arranged for automatic operation.

A 1500 kW. set (consisting of a 1710 kVA., 2300-volt, 50-cycle, 8-pole synchronous motor and two 750 kW., 1500-volt generators) has the following **efficiencies**—

Percentage of full load	50	75	100	125	150
Percentage efficiency	88·6	90·7	91·4	91·5	91·3

A **motor converter,** Fig. 477, consists essentially of a rotary converter connected in cascade with an induction motor. The stator of the induction motor may receive its energy at high voltage, but for supply pressures above 11,000 volts a transformer is employed in conjunction with the induction motor. The rotor of this machine is direct coupled to the armature of the rotary converter. The cascade connection is usually effected by permanent interconnections between tappings on both rotor and armature windings, thereby avoiding slip rings. Fig. 478 shows diagrammatically how these interconnections are arranged in the case of a 12-phase machine. To simplify the starting apparatus only three of the phases of the rotor winding are employed at starting and are brought out to slip rings for connection to the starting rheostat. The full number of phases are connected in circuit by a short-circuiting device (Fig. 479), which is operated after the machine has synchronized.

* Particulars of the South African substations are given in *Journ. I.E.E.*, vol. 66, p. 1026.

The normal operating speed corresponds to the cascade synchronous speed of the combination and is given by Equation (25), p. 122 ; but if the rotary converter loses its excitation the speed of the set increases to practically the synchronous speed of the induction motor.

The **action** is briefly as follows. The slip energy of the induction motor is supplied electrically to the armature of the rotary converter and is converted to the direct-current form. The mechanical output of the induction motor is supplied to the shaft of the rotary converter and is converted into direct-current electrical energy by generator action. Thus the direct-current portion of the set functions partly as a rotary converter and partly as a direct-current generator, the ratio of the energy transmitted to this machine

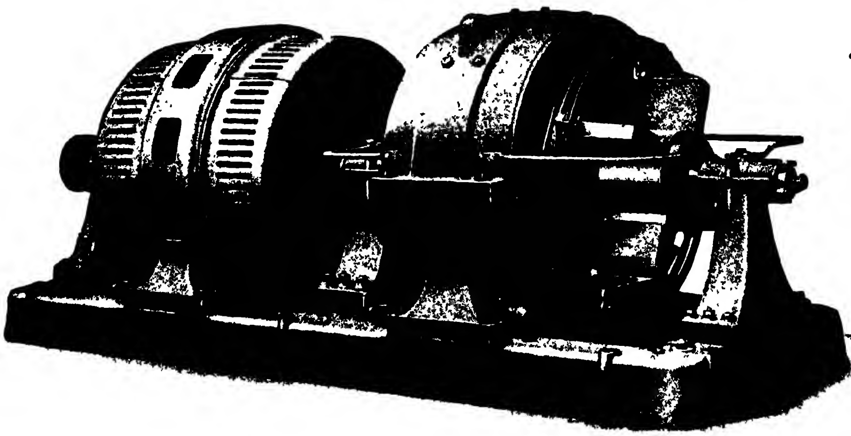


FIG. 477.—B.T.-H. Motor Converter.

electrically and mechanically being equal to the ratio of the numbers of poles in the induction motor and rotary converter [*cf.* Equation (26), p. 122].

The frequency of the electrical energy supplied to the rotary converter is, therefore, only a fraction (viz., $p_2/(p_1 + p_2)$, where p_1 = number of poles in induction motor, p_2 = number of poles in rotary converter) of the supply frequency, and in consequence the machine possesses the following advantages over a rotary converter built for the supply frequency—(1) greater stability with respect to voltage disturbances on the supply system ; (2) practicability of higher commutator voltages ; (3) more extended range of voltage variation by field control and reactance.

Although motor-converters have an extensive application to industrial substations, they have hitherto been employed to a very limited extent in low-voltage traction substations, the rotary converter being usually preferred on account of its higher efficiency and lower cost.

A 1500 kW., 50-cycle, 500 r.p.m. motor converter, for 600 volts D.C. and 6000 volts A.C., has the following **efficiencies**—

Percentage of full load . .	50	75	100	125	150
Percentage efficiency . .	92·5	93·3	93·2	92·7	92·2

MERCURY-ARC RECTIFIERS

General. The mercury-arc rectifier consists essentially of a mercury cathode and a number of graphite or iron anodes enclosed in a highly exhausted bulb or cylinder. The rectifying action is due to electronic emission from a hot spot on the cathode, the conditions upon which this action depends being (1) the maintenance of a high vacuum (0·005–0·001 mm. of

mercury) in the electrode chamber; (2) the maintenance of the high temperature (about 3000° C.) of the cathode hot spot; (3) the prevention of emission from the anodes (i.e. these electrodes must be suitably cooled). The high temperature of the cathode hot spot causes evaporation of the mercury, and therefore means must be provided for condensing the vapour and returning the mercury to the cathode. The presence of the mercury vapour in the electrode chamber gives a low resistance to the electron stream,

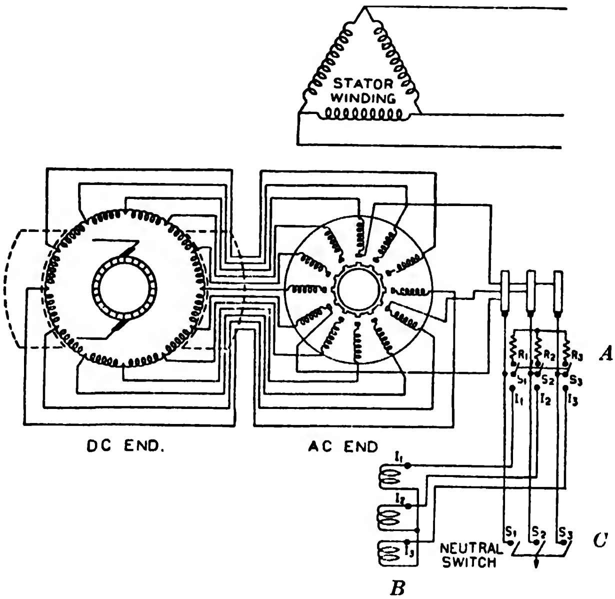


FIG. 478.—Connections of Motor Converter and Starting Gear. (B.T.-H. Co.)

[NOTE.—The starting gear consists of a triple-pole, double-throw switch, A; a star-connected rheostat, R_1, R_2, R_3, of fixed value; and a three-phase choking coil, B. At starting, switch A is thrown "up" (the neutral switch, C, being open) and is thrown "down" when the speed approaches normal. The machine then synchronizes automatically, and the starting operations are completed by short-circuiting the slip rings.]

and enables rectifiers to be built for large outputs with high efficiencies and close voltage regulation.

Construction. The high power rectifier, as developed by Brown, Boveri & Co.* for traction substations, consists of a water-jacketed hermetically-sealed steel cylinder or arc chamber containing the electrodes, and a smaller condensing chamber fitted above. The general arrangement is shown in Fig. 480, in which the mounting of the rectifier upon insulators should be observed.†

* Messrs. Brown, Boveri & Co. have been responsible for the development of the "metal-clad" mercury-arc rectifier. The manufacture of this type of rectifier has recently been taken up by a number of firms in Europe and America. Up to the present time (1929) rectifiers having an aggregate output of nearly 750,000 kW. have been installed by Messrs. Brown, Boveri in traction substations.

† Messrs. Brown, Boveri have recently developed a rectifier in which the cathode is earthed. The installation of such a rectifier on a traction system would be possible if special precautions were taken to avoid leakage currents from the earthed positive return conductor, but in this country the sanction of the Minister of Transport would be necessary. The earthed cathode, however, considerably simplifies the arrangement of the rectifier in the substation, as the insulated base, protecting screens (Fig. 508), and rubber hose connections are eliminated.

The cathode is arranged centrally at the bottom of the arc chamber and is insulated therefrom. The polished iron anodes are fixed in porcelain bushings in the cover plate of the arc chamber, and are arranged symmetrically with respect to the cathode. Six, 12, or 24 main anodes are provided according to the current required; they are supplied with energy from the star-connected secondary winding of a suitable transformer, the neutral point of which forms the negative pole of the direct-current circuit. In all cases two auxiliary anodes (called " excitation anodes ")—which are excited from an auxiliary single-phase transformer and are connected to an auxiliary

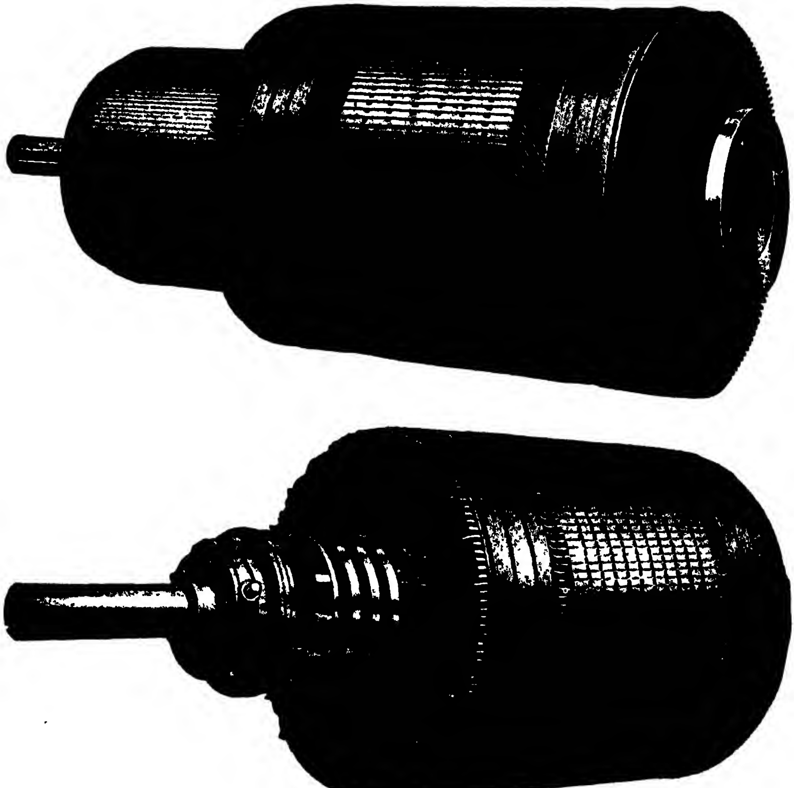


FIG. 479.—D.C. Armature and A.C. Rotor of B.T.-H. Motor Converter.

load—are provided for the purpose of maintaining the temperature of the cathode hot spot when the load on the main anodes falls to zero. Insulated sheet steel funnel-shaped guides and anode shields confine the electron stream or " arc " to definite paths. The anode shields, which are fitted with baffling grids, protect the anode surfaces from ultra-violet rays emitted from the cathode hot spot and from condensation of mercury vapour (both of which would cause internal short circuits or " back ignition "). These guides can be seen in Fig. 481, which shows a rectifier in the final stages of assembly.

The **seals** (which are of extreme importance for preserving the high vacuum essential to the satisfactory operation of the rectifier) are of mercury

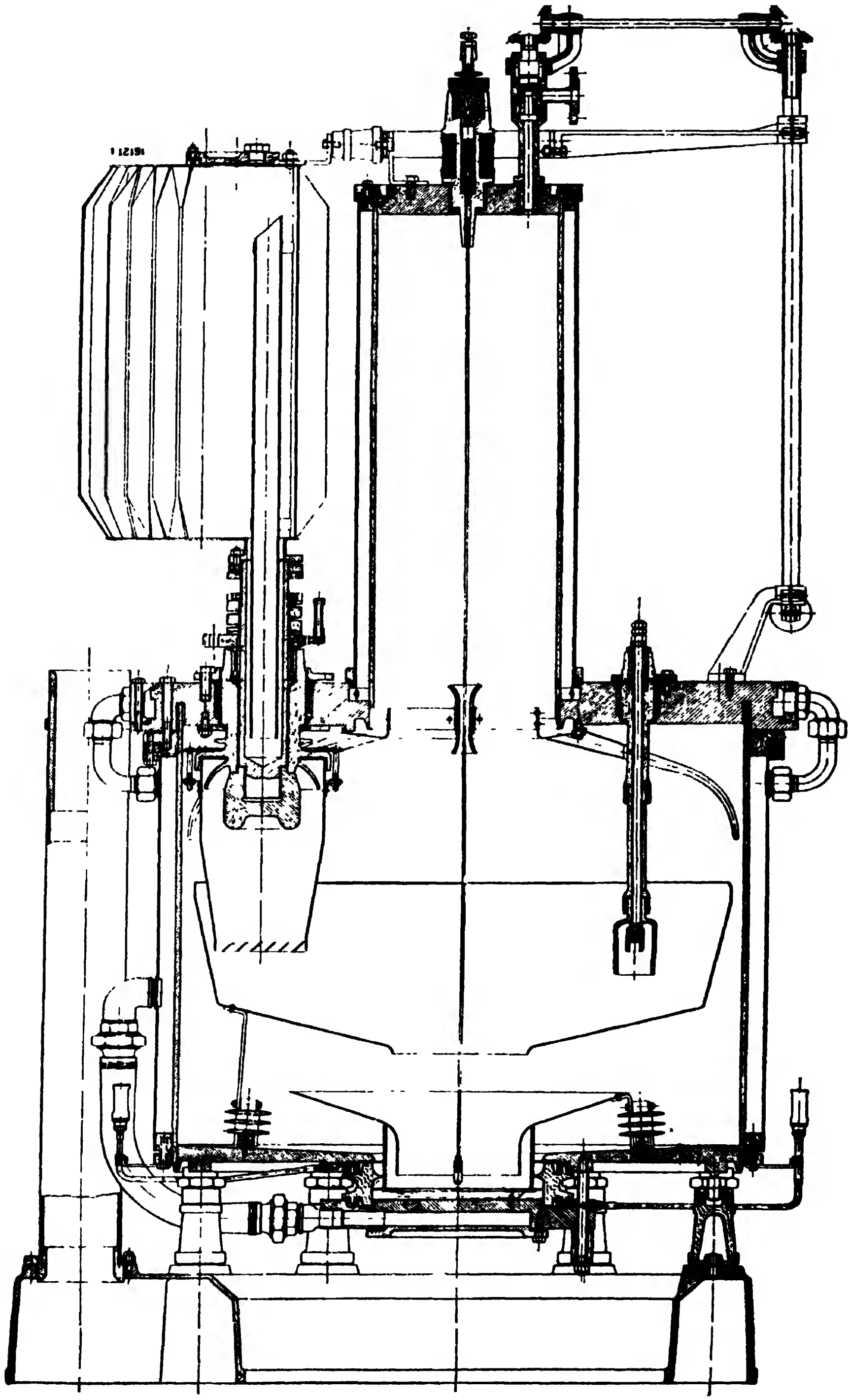


Fig. 480.—Cross Section of Brown-Boveri Rectifier.

A main anode seal is shown in Fig. 482, in which *a* represents the cover plate of the arc chamber; *b*, *c*, the porcelain insulator and asbestos seating pad, respectively; *d*, *e*, the clamping flange and rubber ring, respectively; *f*, the mercury gauge; and *g* the mercury forming the seal. Any leakage at the seal is indicated by a slow sinking of mercury in the gauge *f*, and is remedied by tightening the flange *d*.

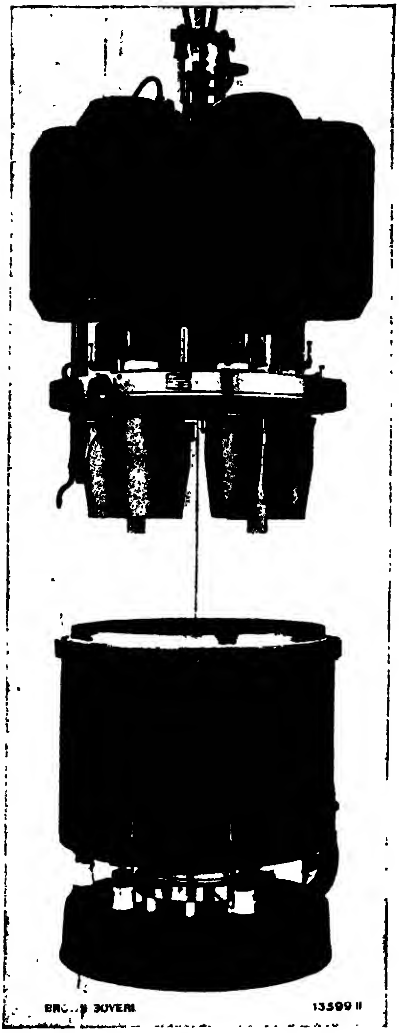


Fig. 481.—Brown-Boveri Rectifier during Assembly.

Initial heating of the cathode is effected by striking an arc at the surface of the mercury by an auxiliary ("ignition") anode, which is normally suspended a short distance above the former. This anode is attached to the end of a long rod, the upper end of which is spring supported from the cover plate of the condensing chamber and is fitted with a plunger-type electro-magnet (Figs. 480, 483), so arranged that when the solenoid is excited the plunger is drawn downwards and the anode is immersed in the mercury.

Cooling of the cathode, arc chamber, and condensing chamber is effected by water jackets and continuous circulation of water, which enters at the cathode and leaves at the top of the condensing chamber. As the cathode is insulated from the arc chamber, a rubber hose, about 50 cm. (20 in.) long, conveys the water from the cathode water jacket to the arc chamber water jacket.

Cooling of the anodes is effected in the smaller sizes by radiating fins attached to the upper ends of the anode rods (Fig. 483), but in the larger sizes water cooling is employed; each main anode being provided with a separate, and self-contained, cooling tank and thermo syphon, as shown in Figs. 480, 481.

Connections. The main connections of a six-anode rectifier are shown in Fig. 484. The transformer has double secondary windings which are connected to form two symmetrical three-phase star groups having a mutual phase difference of 180 degrees. The two neutral points are connected by a centre-tapped choking coil, or inter-phase transformer (also called an "absorption coil"), the centre point of which forms the negative terminal of the direct-current circuit. This coil is wound in sections, which are so connected that (1) the complete winding possesses a high reactance, (2) the direct currents passing in the two halves of the winding produce no resultant magnetisation of the core. Hence the theoretical voltage ratio is the same

as that for a three-phase rectifier. But the pulsations of the load voltage are the mean of those of two three-phase systems 180 degrees apart, and are therefore equal to those of a six-phase rectifier.

This three-phase double-star connection possesses other features. Thus, (1) opposite anodes operate in parallel, and (2) a closed path, internal to the rectifier and transformer, is formed for the circulation of triple-frequency currents (which are due to the triple-frequency E.M.F.'s. existing between the neutral points of the secondary windings). Both of these features result in the voltage drop, due to a given load current, being smaller than that in a six-anode rectifier with the six-phase star connection (i.e. with the two neutral points of the transformer winding solidly connected). Moreover, the three-phase double-star connection is more favourable than the six-phase

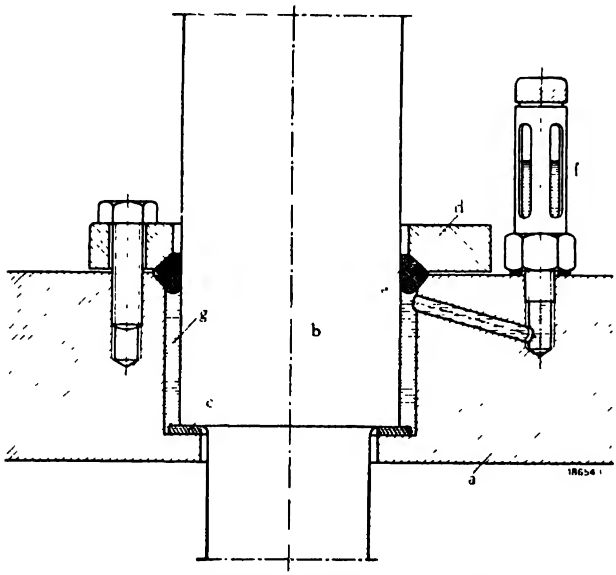


FIG. 482.—Brown-Boveri Anode Seal.

star connection for the design of the transformer, both with respect to power factor and the utilization of copper in the windings.

The connections of the **excitation and ignition** anodes are shown in Fig. 485. Automatic ignition is obtained by means of relays A, B, as soon as the auxiliary transformer is energized. The initial positions of the relays are as shown in Fig. 485, and when the supply is switched on to the auxiliary transformer, the solenoid, E, of the ignition anode is excited, thereby immersing the ignition anode, D, in the cathode mercury bath, C, and establishing a circuit through the auxiliary load, the resistance R_1, and the relay operating coils. Relay B, which is adjusted to operate with a smaller current than A, opens the circuit of the solenoid E, and the ignition anode is withdrawn by the spring S. If the arc is of correct polarity the excitation anodes come into action, and the increased current in the auxiliary load circuit causes relay A to open the circuit of the ignition anode. If the initial arc is not of the correct polarity, the excitation anodes do not come into action and the initial arc is immediately extinguished, causing relay A to re-close and re-ignition to take place.

Voltage ratio. The theoretical voltage ratio is easily calculated if the voltage drops in the arc and other parts of the circuit are ignored, and the

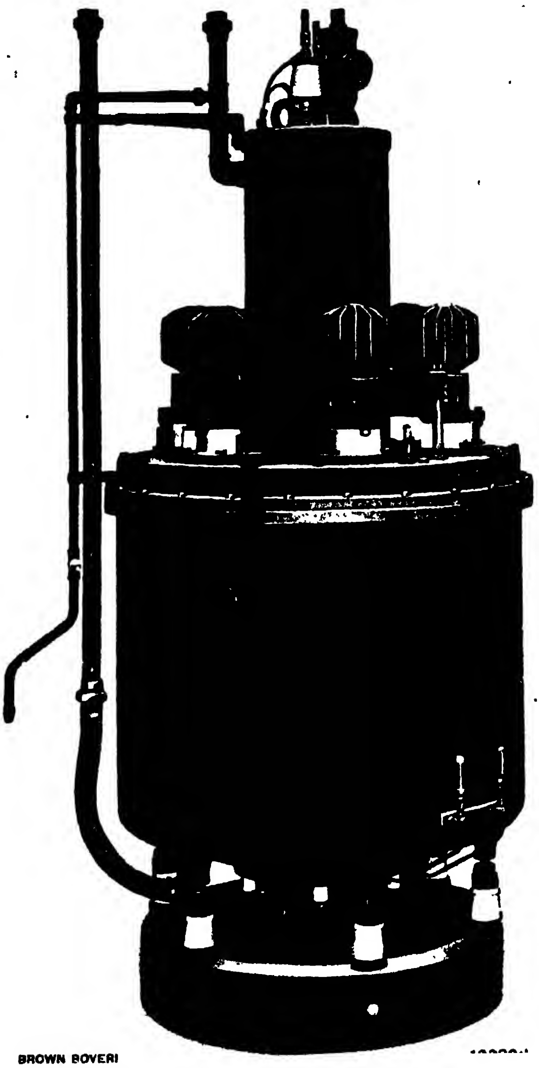


FIG. 483.—Brown-Boveri 700-Ampere Rectifier.

alternating voltages follow sine laws. Thus, if n is the number of phases in the secondary system supplying the anode, E_a the r.m.s. value of the E.M.F. of each phase, $2\pi/n$ the mutual phase difference between the several E.M.F.'s.

the output voltage (E_d) is the mean value of the phase E.M.F. taken over an interval π/n on each side of the maximum value, i.e.—

$$E_d = \frac{n}{2\pi}\int_{-\pi/n}^{+\pi/n} \sqrt{2}\,.\,E_a \cos \omega t\,.\,d\omega t = \left(\sqrt{2}\,E_a \sin\frac{\pi}{n}\right)/\frac{\pi}{n}$$

Whence $$E_d/E_a = [\sqrt{2}\sin(\pi/n)]/(\pi/n) \qquad (67)$$

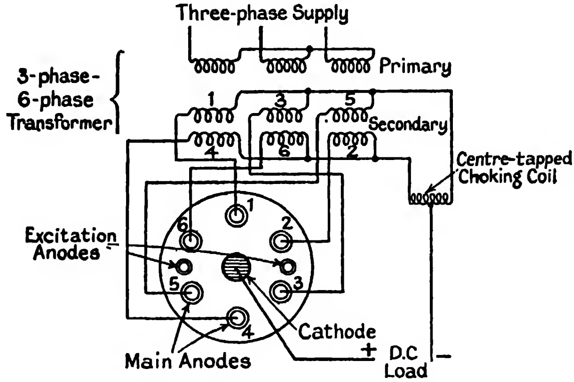


FIG. 484.—Main Connections of Six-anode Rectifier

The values of this quantity are—

0·9 for a single-phase rectifier (2 anodes)
1·17 for a three-phase rectifier (3 anodes)
1·17 for a double three-phase rectifier (6 anodes)
1·35 for a six-phase rectifier (6 anodes)
1·4 for a twelve-phase rectifier (12 anodes)

Accessories. The accessories necessary for a rectifier plant are (1) main and auxiliary transformers, (2) vacuum pumps, (3) water cooling system.

The **main transformer** for a rectifier is of larger size than that for a rotary converter of the same output, owing to the unfavourable utilization of the copper in the secondary windings, due to the intermittent nature of the phase currents. For example, each section of the secondary winding supplying a six-anode, six-phase rectifier is in action for one-sixth of a period, and the r.m.s. value of the current in any section is 2·45 ($= \sqrt{6}$)* times the mean value. With the three-phase double-star connection each section of the secondary winding is in action for one-third of a period, and the r.m.s. value of the current in any section is 1·73 ($= \sqrt{3}$) times the mean value.

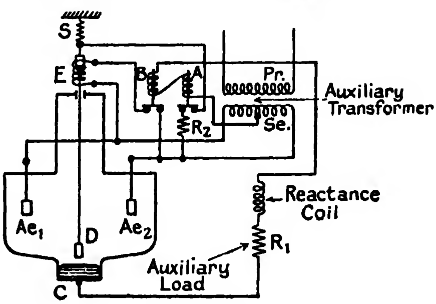


FIG. 485.—Connections of Excitation and Ignition Circuits of Brown-Boveri Rectifiers.

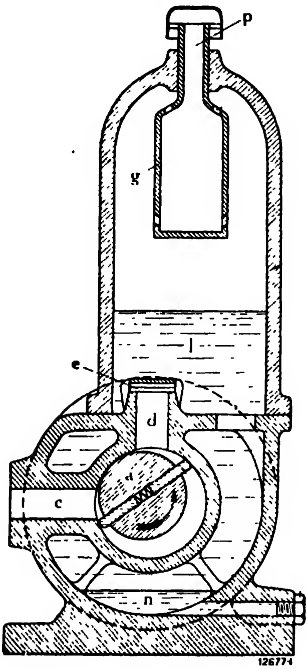
On the other hand, the windings of a transformer supplying a rotary

* If the wave form of the anode currents is rectangular, and if n = number of anodes, I_d = current output from cathode, the r.m.s. value of the phase current $= \sqrt{[(I_d^2 2\pi/n)/2\pi]} = I_d/\sqrt{n}$, and the mean value of the phase current $I_d(2\pi/n)/2\pi = I_d/n$. Whence r.m.s. value/mean value $= \sqrt{n}$.

converter are in action for the whole period, and if the currents follow sine laws the r.m.s. value is $1{\cdot}11 (= \pi/(2\sqrt{2}))$ times the mean value.

Usually the kVA. rating of a transformer for a rectifier is from $1\frac{1}{3}$ to $1\frac{1}{2}$ times the kW. output from the direct-current side, whereas the kVA. rating of a transformer for a rotary converter is about 1·1 times the kW. output of the machine.

The **auxiliary transformer** is of the three-phase type and is supplied direct from the primary distribution system. This transformer supplies three-phase energy to the vacuum-pump motor and single-phase energy to



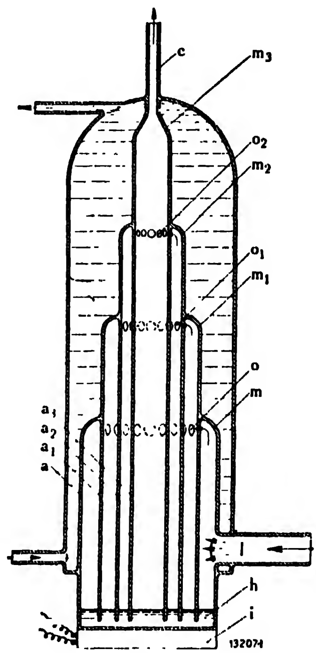


Fig. 486. Fig. 487

Arrangement of Brown-Boveri Mechanical and Ejector Pumps.

References to Fig. 486: *a*, impeller; *c*, suction port; *d*, exhaust port with non-return valve, *e*; *g*, separator; *p*, exhaust outlet to ejector pump; *n*, sump.

the other auxiliary circuits (viz. excitation, ignition, ejector (mercury-vapour) pump, vacuum gauge). Single-phase transformers are necessary for the excitation and ignition circuits (Fig. 485), and for the vacuum gauge (Fig. 489) and ejector pump.

Vacuum pumps. The high vacuum, of 0·005 mm. mercury, is produced and maintained by a pump set, which consists of a mechanical pump working in series with a mercury-vapour ejector pump.

The mechanical pump, Fig. 486, is of the oil-immersed rotary type and is coupled to a $\frac{1}{2}$ h.p. driving motor by an insulating coupling. The motor is insulated from the pump frame, which is also mounted upon insulators as shown in Fig. 488. An oil-sealed automatic valve, fitted to the suction port of the mechanical pump, prevents loss of vacuum when the pump is shut down.

The mercury-vapour ejector pump consists of a number of concentric vertical tubes, a, a_1, . . ., Fig. 487, of graduated lengths, with their upper ends closed and water-jacketed, and their lower ends immersed in a heated

mercury bath, h. The annular chambers thus formed have a series communication with one another by means of the holes σ, σ_1, σ_2. The outermost chamber is connected to the condensing chamber of the rectifier; the gases enter this chamber at l and are drawn upwards by the mercury vapour rising from the bath h, the exhaustion products being ejected through the holes σ to the second and succeeding chambers. These products finally leave at c and pass to the mechanical pump. The mercury bath is heated electrically by the heater i (rated at 1 kW.).

Vacuum gauge and automatic control of vacuum pump. The state of the vacuum in the rectifier is indicated continuously by a switchboard-type electrodynamic instrument (calibrated over a range 0·01 to 0·001 mm. mercury) which operates in conjunction with a Wheatstone network of heated platinum wires, the principle of operation depending upon the physical law that the heat conductivity of a gas is a function of its absolute pressure. Two of the wires A, B, Fig. 489, are enclosed in sealed glass tubes connected to a tee in the vacuum main, and the other two wires C, D are exposed to the air. Hence, if the network is balanced when cold, it will become unbalanced if the wires are heated by a current led into the junctions 1 and 3, and a difference of potential will exist between the junctions 2 and 4.

The heating current is usually supplied by a transformer, and is maintained constant by means of a ballast resistance of iron wire enclosed in a tube containing hydrogen. The indicator is usually fitted with contacts which control the heater of the mercury bath and the motor driving the mechanical pump.

Cooling water. The method of circulating the cooling water depends upon the quantity of water available, its quality and the voltage of the direct-current side. A closed-circuit system, with pump circulation and forced draught, is shown diagrammatically in Fig. 490. Such a system is employed exclusively in plants where the voltage exceeds 2000 volts and for other installations where water is scarce or impure. In these plants the cooler, RA, and the circulating pump, P, are mounted upon insulators, and lengths of rubber hose, m, are inserted between the flow and return pipes a, b, and the rectifier, GR. The cooler consists of a series of tubes exposed to an air blast produced by a fan. Provision is made for direct cooling from the main water supply system, g, when the cooler is shut down for cleaning or repairs; the flow pipe, a, being connected, by the rubber hose p, and valves, σ, directly to the water supply, g, the valve i being closed. In these circumstances the outlet from the rectifier water jacket discharges into the drain f by means of the pipe c and the valve d.

Operating features. The voltage drop between the electrodes of the rectifier is about 25 volts and is practically constant at all loads. Hence, as this constitutes the only loss in the rectifier itself, the theoretical efficiency (neglecting the excitation circuit) is a function of the output voltage. For example, for output voltages of 600, 1500, and 3000 the theoretical efficiencies are (600/625 =) 0·96, (1500/1525 =) 0·984, and (3000/3025 =) 0·992. When the losses in the transformer, and the power supplied to the auxiliary circuits, are taken into account, the overall efficiencies are—

1. 600-volt plant—1000 kW. rectifier supplied from 10,000-volt, 50-cycle, three-phase system—

Percentage of full load .	25	50	75	100	125	150
Percentage of efficiency.	93·3	94·8	95	94·1	92·8	91·5

2. 1500-volt plant—1000 kW. rectifier supplied from 10,000 volt, 50-cycle, three-phase system—

Percentage of full load .	25	50	75	100	125	150
Percentage efficiency .	93·8	95·5	95·8	95·7	95·6	95·5
Percentage power-factor	80	89	94·5	96	96·5	96·2

Owing to the relatively low light-load losses the all-day efficiency of a traction substation equipped with rectifiers is much higher than that of a similarly loaded substation equipped with rotating converting machinery. This higher all-day efficiency results in a very considerable annual saving of energy. For example, tests on motor generators (650 kW., 2 × 2000 volts) and a rectifier (800 kW., 4000 volts) in the Ciriè substation of the Turin-Ceres (interurban) Railway (4000 volts) gave the following results for a normal day's (20 hour) working in each case—

Date of test	16th July, 1924	16th July, 1925
Energy output (kWh.)	6050	6050
Energy input to motor-generators (kWh.)	7617	—
Energy input to rectifier (kWh.)	—	6435
All day efficiency (per cent)	79·5	94

Again, tests carried out on the substations of the Chicago, North Shore and Milwaukee Railroad (five of which are equipped with 1000–1500 kW., 600-volt, rotary converters, and one is equipped with a 1000 kW., 600-volt rectifier) gave the average all-day efficiency of the rotary converter substations as 73·4 per cent, and that of the rectifier substation as 81·7 per cent.*

The instantaneous **overload capacity** of a rectifier is very large, and the permissible short-time and sustained overload periods for the combination of rectifier and transformer are usually

Per cent overload	200	100	50	25
Duration (minutes)	1	5	15	30

If desired, a longer duration of the overload period can be obtained (e.g. some rectifier plants are designed to operate at 50 per cent overload for 2 hours and 200 per cent overload for 5 minutes).

The **voltage characteristic**, or regulation curve, resembles that of a shunt generator. The percentage voltage drop from light load to full load depends upon the connections employed and the impedance voltage of the transformer. A value between 3·5 and 5 per cent is representative for a double three-phase rectifier.

A flat compound or over compound characteristic may, however, be obtained by means of a specially wound interphase transformer (or absorption coil) in which the load current causes magnetic saturation of the core. Hence, at heavy loads a large diminution occurs in the reactance of the winding connected between the neutral points of the secondary windings of the main transformer. Thus the rectifier operates as a double three-phase rectifier (for which the theoretical voltage ratio is 1·17) at light loads, and as a six-phase rectifier (for which the theoretical voltage ratio is 1·35) at heavy loads. The method has the disadvantage of adversely affecting the power factor.

Adjustment of the output voltage, if required, is effected by tappings on the primary winding of the transformer. When continuous adjustment is necessary an induction regulator is employed.

Parallel operation of rectifiers with rotary converters and motor generators presents no practical difficulties; but to utilize fully the constant-efficiency characteristic of the rectifier the voltage characteristics of the machines and rectifiers should be so arranged that the machines operate at a steady load and that fluctuations of the load are taken by the rectifiers.

The **principal advantages** of a rectifier plant over a converting plant consisting of rotating machines are briefly—(1) high efficiency over the whole working range; (2) ability to supply large momentary loads; (3) insensibility to short circuits; (4) extremely simple and quick starting; (5) noiseless

* Operation and performance of mercury-arc rectifier on the Chicago, North Shore and Milwaukee Railroad," by Caesar Antoniono. *Trans. A.I.E.E.*, vol. 47, p. 228.

operation ; (6) minimum attention ; (7) low maintenance cost ; (8) reliability of service ; (9) lighter foundations and smaller substation building. The

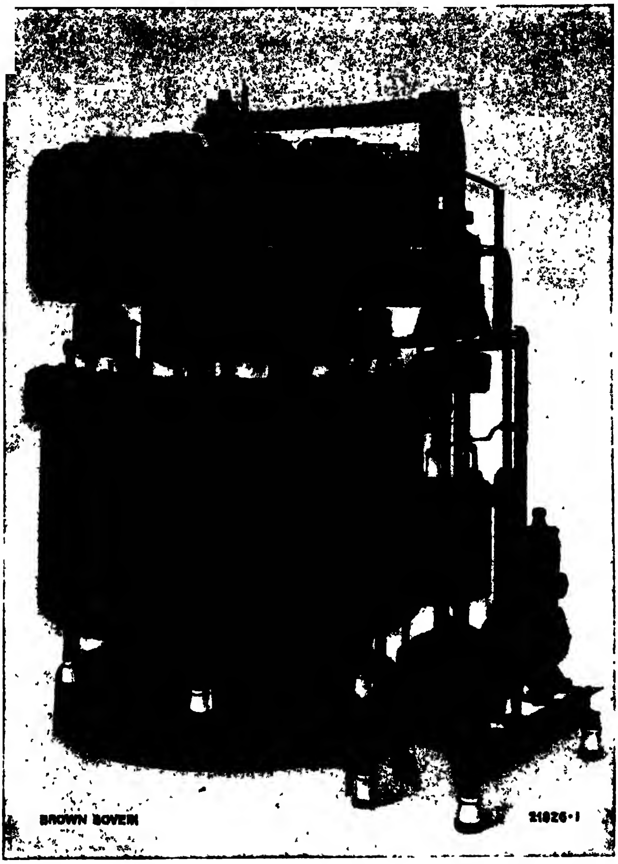


FIG. 488.—Arrangement of Brown-Boveri 1000 kW., 1750 A., Rectifier and Pump Set.

chief disadvantages are—(1) lower power factor, (2) distorted wave-form of supply current ; (3) pulsations in output voltage and current.

DISTRIBUTION SWITCHGEAR FOR TRAMWAYS AND DIRECT-CURRENT RAILWAYS (ATTENDED SUBSTATIONS)

Substations containing converting machinery require switchgear for controlling (*a*) the incoming and interconnecting feeders, (*b*) the converting machinery, (*c*) the distribution network. As the switchgear for items (*a*) and (*b*) does not present any special features for traction service, we shall consider only that for the distributing system.

Switchboards for overhead tramways comprise (1) line, or positive, feeder panels ; (2) track, or negative, feeder panels ; (3) a testing panel.

The line (positive) feeder panels are generally equipped with an automatic overload circuit-breaker, an ammeter, and a single-pole switch.

The track (negative) feeder panel equipment varies according to circumstances. In cases where negative boosters and a number of track feeders are installed, switchgear is usually provided in the form of vertical and horizontal bars with connecting plugs, to enable any track feeder to be connected to any booster. The line feeders and the (series) field windings of the boosters are arranged in a similar manner, so that the line feeder corresponding to a given track feeder may be connected in series with the field winding of the booster to which the track feeder is connected.

The **testing panel** (formerly called the "Board of Trade" panel) is equipped with (1) a recording voltmeter (0–10 volts) for recording the potential difference between given points in the rail, (2) a double-range ammeter (0–0·05 ampere, 0–5 ampere) for measuring the leakage current and for testing the conductivity between the earth plates. The connections are shown in Fig. 491. When switch X is thrown to the right, the higher range of the ammeter is connected in series with a four-volt battery to the earth plates. When this switch is thrown to the left, the lower range of the ammeter is connected to the multi-contact switch Y, which is connected to the line feeders.

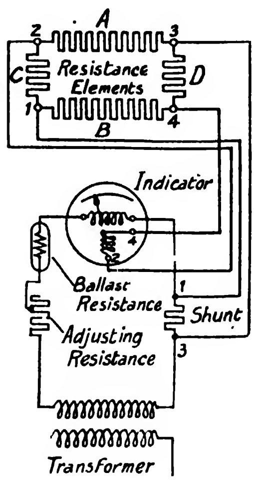


FIG. 489.—Connections of Brown-Boveri Vacuum Gauge.

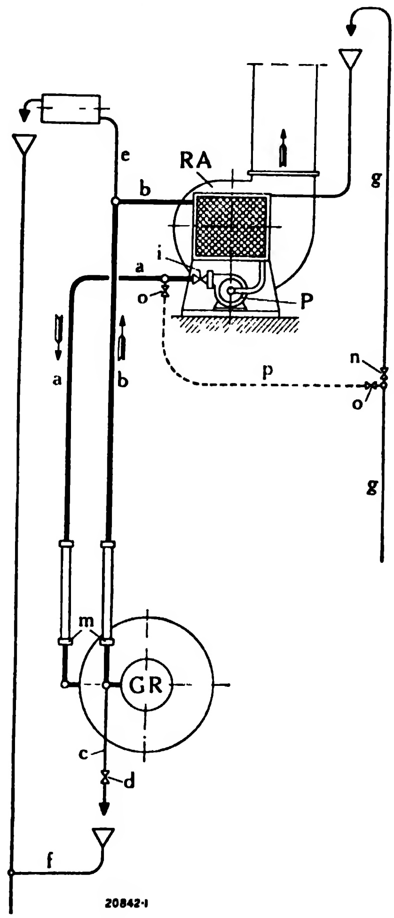


FIG. 490. Closed Circuit Water Cooling System for Rectifier. (Brown-Boveri.)

In some cases a recording ammeter (range 0-20 amperes) is provided for recording the current returning to the negative bus-bar via the earth plates, but usually a maximum demand indicator is used for this purpose, and is located in the feeder pillars (p. 626).

Switchboards for conduit tramways comprise (1) feeder panels, (2) a testing panel. As equal numbers of positive and negative feeders are

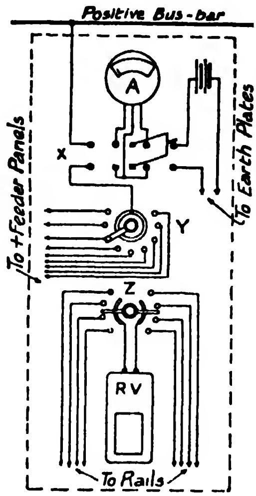


FIG. 491.—Connections of Testing Panel for Overhead Tramways.

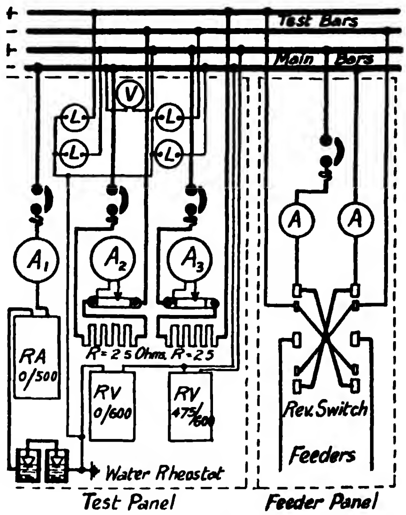


FIG. 492.—Connections of Feeder and Testing Panels (L.C.C. Conduit Tramways).

employed, each feeder panel is equipped with a double-pole switch, two ammeters, and a single-pole overload circuit breaker.

To enable the *nature* of faults to be detected, the switches on the feeder panels of the London County Council conduit tramways are of the reversing type and are fitted with auxiliary contacts, which are insulated from the main contacts and are connected to a special pair of "testing" bus-bars. These bus-bars may be connected to the main bus-bars through metallic resistances (totalling approximately 5 ohms), ammeters, and circuit breakers mounted on a "test" panel, as shown in Fig. 492. The main negative bus-bar is earthed at each substation through indicating and recording ammeters, A_1, RA, and a water rheostat (about 1 ohm).

A fault on the positive side of the system is shown by a change in the brightness of the lamps, L, on the test panel and by the opening of the circuit breaker on the feeder panel.

A fault on the negative side is shown by unequal readings of the ammeters on the feeder panel. In order to locate a car which has a negative fault, the polarity of one section of the track is reversed, and as the car enters that section the fault is transferred to the positive side, thereby opening the feeder circuit breaker.

In the event of a feeder circuit breaker opening (due to a positive fault, or a fault between the conductor rails), the appropriate feeder

switch is withdrawn into the auxiliary contacts, and the circuit breakers on the test panel are closed. The magnitude of the fault is then shown by the indications of the ammeters on the test panel, A_2, A_3. If the switch is then thrown to the lower auxiliary contacts the fault is shown as " clear " if it is on the positive side, but as " uncleared " if it is a fault between the conductor rails.

With a positive fault the service can be maintained by temporarily reversing the polarity of the conductor rails of the section on which the fault has occurred (e.g. by placing the feeder switch in the lower main contacts). In these circumstances the resistance in the negative bus-bar earth connection would be increased, so as to limit the current returning to the station via earth.

The leakage tests (see Regulations, p. 686) are carried out by placing the feeder switches—one at a time—in the auxiliary contacts and noting the indications on the ammeters A_2, A_3, on the test panel, a suitable range being provided for this purpose.

Switchboards for low-voltage direct-current railways are generally similar to those for overhead tramways, except that, as no negative boosters are employed, only panels for the conductor-rail feeders are required. In the case of railways having positive and negative conductor rails, each feeder panel is equipped with two single-pole circuit-breakers, two single-pole switches, and an ammeter. When the track rails are used as the return, each feeder panel is equipped with a single-pole circuit breaker, a switch, and an ammeter. The negative feeders from the track rails are generally connected directly to the negative bus-bar.

A typical switchboard is shown in Fig. 493, and comprises four feeder panels (each controlling two positive feeders) and three machine panels (each controlling a rotary converter).

Switchboards for high-voltage direct-current railways must be equipped with remote-operated switches and circuit breakers, together with shielded instruments, in order to safeguard the operators. The switches and circuit breakers are mounted out of reach at the top of the panels, and are operated by insulated rods and bell cranks from hand levers mounted at a convenient height on the panel. A typical switchboard is shown in Fig. 494.

SWITCHGEAR FOR UNATTENDED (AUTOMATIC) SUBSTATIONS

General. Unattended substations equipped with either rotating converting machinery or mercury-arc rectifiers have an important application on traction systems. Such substations are now commercial propositions, and although more costly initially than attended substations, they result in a considerable annual saving compared with attended substations.

With tramways, interurban, and main lines, fully automatic operation is desirable, the substation coming into service in response to a demand for power, and falling out when the demand ceases. With heavy suburban traffic, however, supervisory control is preferable, the non attended substation being controlled from either an attended substation or the train dispatcher's office.

In all cases when a feeder is cut out of service due to a temporary short circuit, the supply must be restored automatically as soon as the

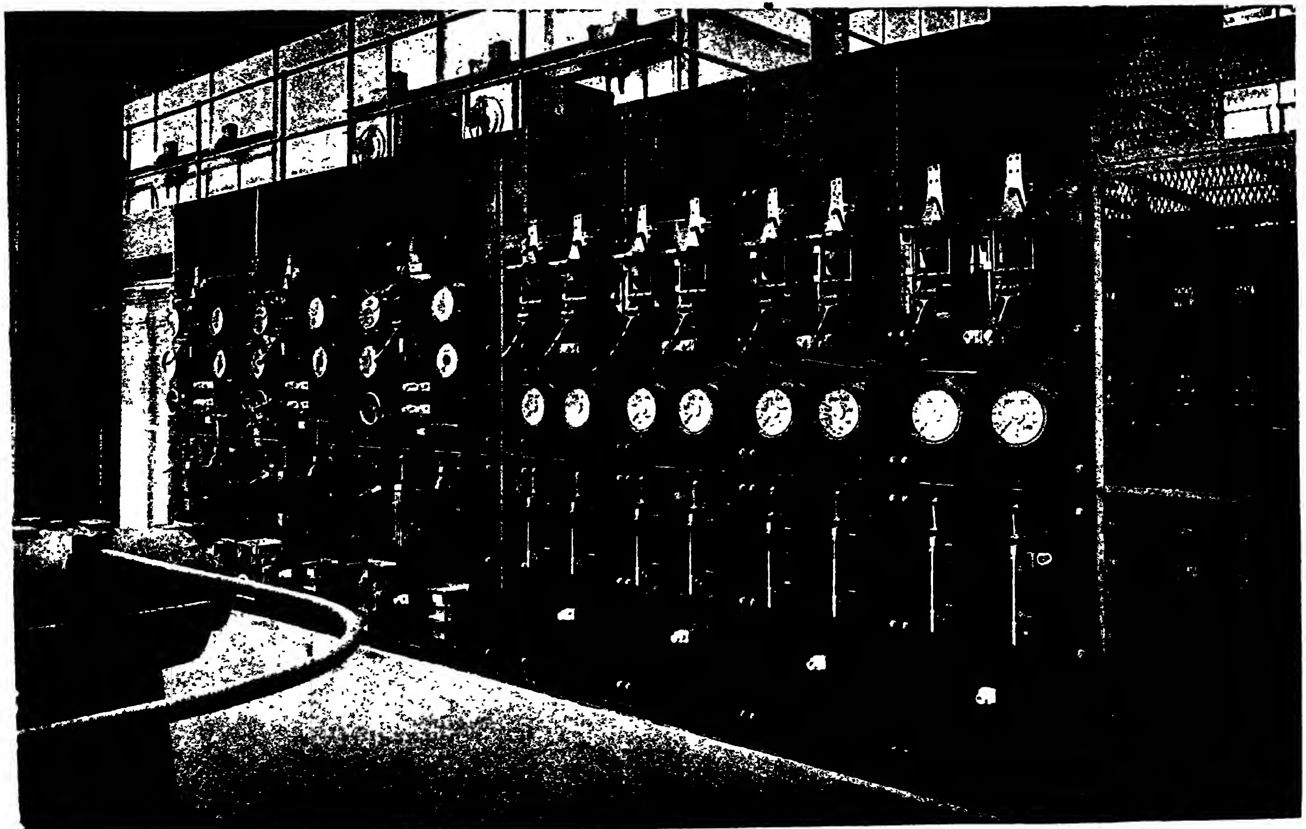


FIG. 493.—Switchboard for Controlling Rotary Converters and Conductor-rail Feeders (Southern Railway). [B.T.-H. Co.]

short circuit has cleared. But in the event of a permanent short circuit the feeder must remain "dead." Moreover, in many cases it is desirable that the feeder protective gear should discriminate between short circuits and sudden overloads due to heavy demands for power. These features are obtained by means of electrically-operated automatic re-closing circuit breakers in conjunction with special relays.

Automatic switchgear for direct-current feeders. This switchgear comprises (1) an electrically-operated circuit breaker, (2) relays for controlling the closing and tripping of the circuit breaker.

The simplest method of operation (which gives no discrimination between short circuits and legitimate sudden overloads) is to arrange that when the circuit breaker opens, due to an overload or short circuit, it is re-closed again automatically after a short time delay. If the circuit breaker re-opens, it is re-closed again, and, if necessary, the cycle is repeated for a pre-determined number of times, when, if the fault still persists, the circuit breaker is locked out. This action is obtained by means of a time delay repeat action relay, which automatically re-sets if the circuit breaker remains closed for a predetermined time interval, but requires to be re-set by hand when the circuit breaker is locked out.

Fig. 495 shows such an equipment installed in an unattended substation on a suburban railway. In this case the circuit breakers are of the high-speed, or quick-acting, type and are located on a gallery above the switchboard. The closing coils of these circuit breakers are controlled by the four small double-pole contactors mounted on the upper portion of the centre panel.

One form of high-speed circuit breaker is shown in Fig. 496, and the following special features are embodied in the design—(1) extremely high speed of opening for any rate of rise of current; (2) electromagnetic release not involving latched parts; (3) powerful magnetic blow-out with narrow arc chute. Such a circuit breaker can clear a severe short circuit on a 600-volt system in about 0·01 sec., whereas about 0·15 sec. would be required with an ordinary circuit breaker. Moreover, the current peak when a short circuit is cleared by a high-speed circuit breaker is only about 50 to 60 per cent of that when an ordinary circuit breaker is employed under similar circuit conditions.

Discrimination between short circuits and sudden overloads is obtained by a current transformer and a quick-acting relay, the latter controlling the tripping circuit of the circuit breaker. The primary winding of the current transformer is connected in series with the feeder and the secondary winding is connected to the relay. The operation of the relay therefore depends upon the *rate* of increase of current in the feeder and the duration of the transient effect. Such a device gives satisfactory service in cases where the circuit conditions are suitable, but in some cases (e.g. with very heavy suburban railway service) difficulty may be experienced in obtaining sufficient discrimination between short circuits and heavy demands for power.

Automatic re-closing of a feeder circuit breaker upon the clearance of a fault is obtained by means of a load resistance relay and an auxiliary bridge network of fixed resistances. The operation of the relay is dependent upon the combined resistance of the load and fault. If this resistance

Fig. 494.—1200 Volt Direct-Current Switchboard (London, Midland and Scottish Railway). [B.T.-H. Co.]

exceeds a predetermined value the relay causes the circuit breaker (which is assumed to have opened due to a temporary short circuit) to re-close, but if the resistance is below this value the relay prevents the re-closing of the circuit breaker.

A schematic diagram of the circuits is shown in Fig. 497. The closing coil of the circuit breaker (40) is controlled by a small contactor (40 A),

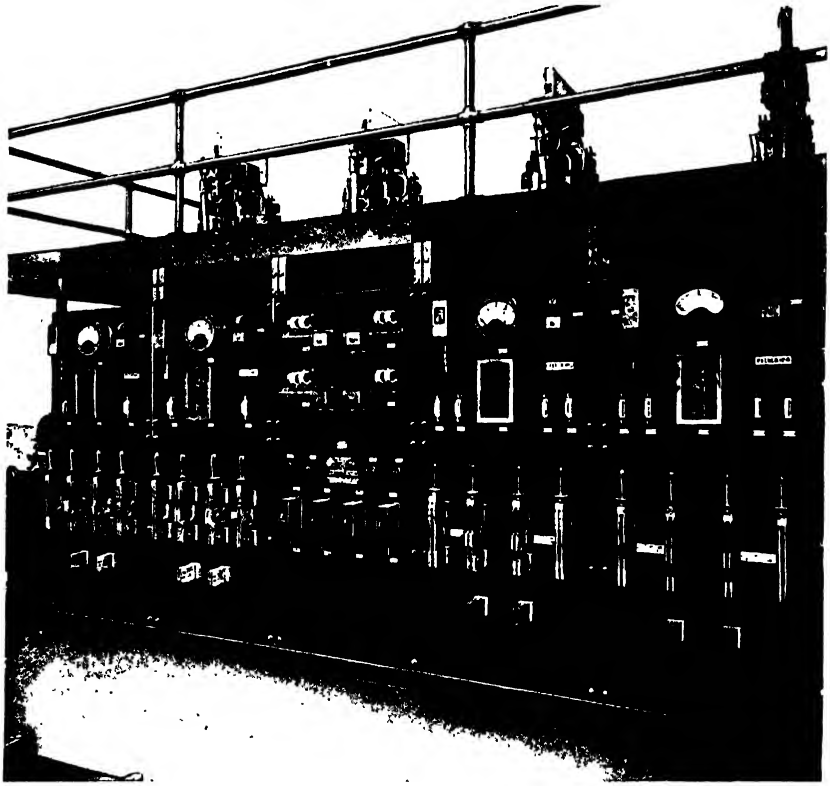


FIG. 495.—Feeder Panels in Unattended Railway Substation, with Automatic Re-closing High-Speed Circuit Breakers. (B.T.-H. Co.)

the operating coil of the latter being connected in parallel with the contacts of the short-circuit discriminating relay (50), the re-set coil (50 R) of which is controlled by the load-resistance relay (42).

When the circuit breaker opens, the auxiliary resistances are connected in series with the feeder, and an auxiliary switch on the circuit breaker closes the operating coil of contactor (47), the contacts of which close after a short time delay and connect the relay (42) to the bridge network. If the combined resistance of the load and fault is below a predetermined value the current passing through the relay (42) will be insufficient to operate its contacts, and in consequence the feeder circuit breaker will remain open, due to the contacts of relay (50) shunting the coil of contactor (40 A). But as soon as the fault clears, sufficient current passes

through relay (42) to close its contacts. The re-set coil of relay (50) is therefore actuated and the short circuit across the operating coil of contactor (40 A) is removed, thereby allowing the circuit breaker to re-close.

Automatic switchgear for converting machinery. The switchgear which effects the automatic starting and stopping of the converting machinery in an unattended substation comprises (1) the master control devices, which cause the substation to come into action or to drop out according to the power demand; (2) the apparatus for effecting the starting operations and connecting the machines to the load; (3) the protective devices.

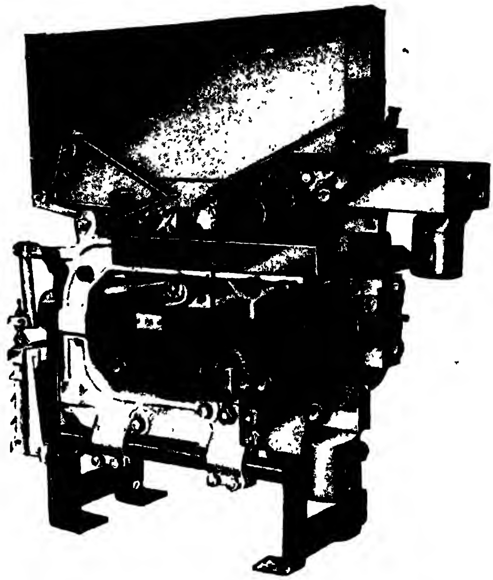


Fig. 496.—B.T.-H. High-Speed Circuit Breaker.

With fully automatic substations the master starting device is a relay which closes its contacts when the voltage at the direct-current busbars falls below a predetermined value. These contacts are connected in series with those of a time-delay relay, the object of which is to prevent the premature starting of the machine due to momentary fluctuations of line voltage. The master stopping device is an underload

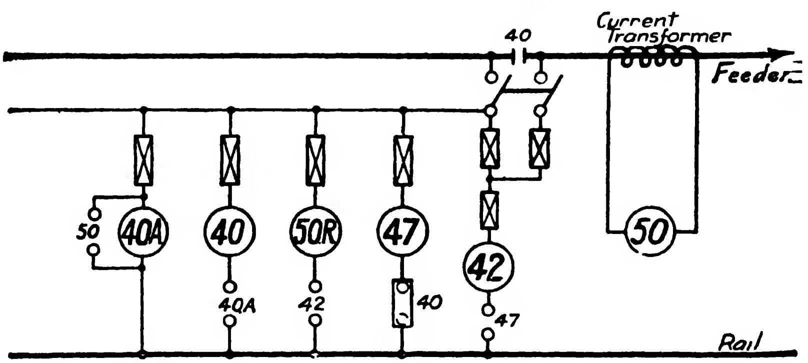


Fig. 497.—Schematic Diagram showing Connections for Automatic Re-closing Circuit Breaker for Feeder. (Metropolitan Vickers.)

Reference: 40, circuit breaker; 40A, auxiliary contactor; 42, relay; 47, auxiliary contactor; 50, discriminating relay; 50R, re-set coil for 50. For key to symbols see Fig. 500.

relay connected in the direct-current circuit, this relay also operating in conjunction with a time-delay relay.

The starting operations in the case of rotary converters involve

starting and synchronizing, determining the polarity of the direct-current side and correcting this if necessary. Alternatively, correct polarity may be obtained directly by separately exciting, temporarily, the machine. The machine may be started either from tappings on the transformer or

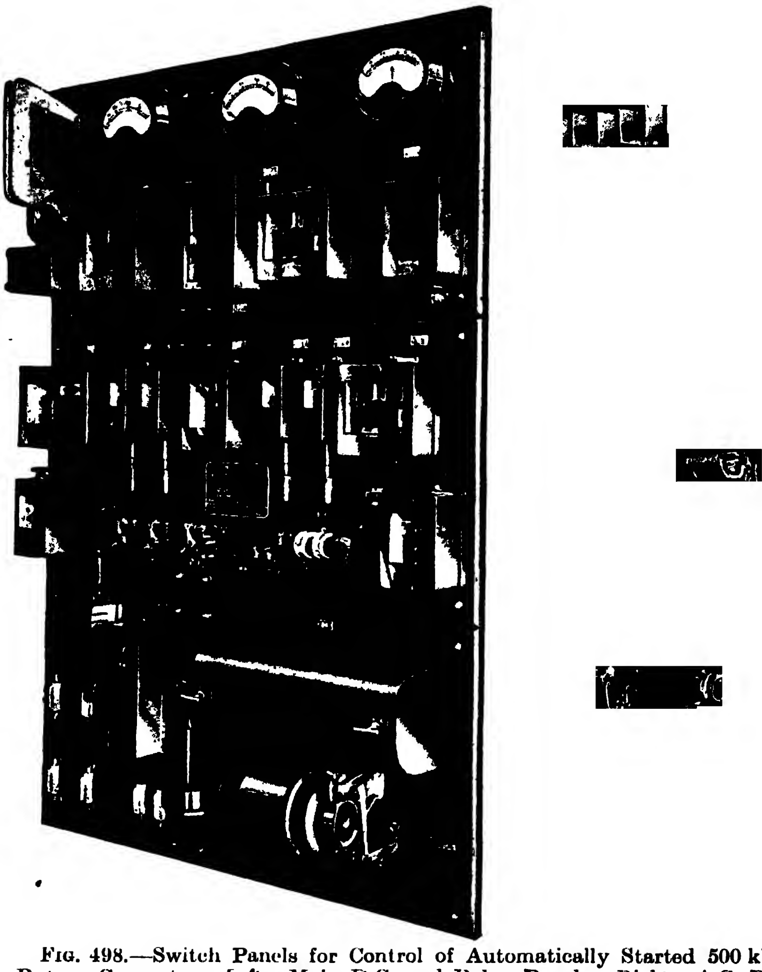


FIG. 498.—Switch Panels for Control of Automatically Started 500 kW. Rotary Converter. *Left.* —Main D.C. and Relay Panels. *Right.*—A.C. Panel. (B.T.-H. Co.)

by a starting (induction) motor, but with tap starting the brushes, except two pilot brushes, must be raised from the commutator in order to avoid sparking during starting. The starting operations are effected by means of contactors and relays, and the correct sequence of these operations is ensured either by interlocks on the contactors and relays or by a motor-driven drum-type master controller. Fig. 498 shows the relay and contactor panels for a typical installation, and Fig. 499 shows the master controller.

The protective devices, in addition to giving protection against overload, reverse current, and over speed, must provide against the following—(1) hot bearings; (2) hot machine or transformer windings; (3) overheating of the load-limiting rheostats; (4) single-phase operation; (5) reversal of phase rotation; (6) flash-overs from brush gear to frame; (7) incorrect polarity; (8) failure of excitation; (9) abnormal voltages on the alternating-current side; (10) short circuits internal to the machine or transformer. In cases of trouble due to causes (2), (3), (4), (5), (9) the machine is shut down temporarily, but in the event of trouble due to causes (1), (6), (8), (10) the machine must be shut down until the cause of trouble has been investigated.

Fig. 499.—Master Controller for obtaining Correct Sequence of Operations during Automatic Starting of Rotary Converters. (B.T.-H. Co.)

Example of starting operations for automatically started rotary converter. A schematic diagram of connections is shown in Fig. 500 and refers to a machine with a starting (induction) motor. The starting operations are controlled entirely by relays in accordance with the practice of the Metropolitan Vickers Co. The time taken to complete the sequence of starting operations varies between limits not exceeding 35 to 55 seconds, depending upon whether the machine excites with correct or incorrect polarity. Assuming that the single-pole change-over switch (17) is in the "auto" position and that the isolating switches are closed, the automatic operations are, briefly—

1. Low voltage on the direct-current side, consequent upon a demand for power, causes relay 1 to close and energize the time-delay relay (2) via an auxiliary switch on the main oil switch (20.)

2. If the low voltage persists, the master relay (3A) and the auxiliary relay (3) are energized in succession, provided that the phase rotation is correct (in which case the contacts of relay (18) are open). Voltage is thereby applied to the main control bus-bar (*A*1), and a retaining circuit is established for the master relay (3A) in order that further operations shall be independent of the voltage at the direct-current bus-bars.

3. The application of voltage to the main control bus-bars energizes relay (4x) thence auxiliary contactor (4), which energizes the closing coil of the starting contactor (34), and also the control relay (21x) of the main oil switch (20). Relay (21x) controls an auxiliary contactor (22), which in turn controls the closing coil of the oil switch (20). When this switch closes, and is latched, an auxiliary switch energizes the low-voltage release (20A) and a time-limit relay (21), the latter causing the removal of power from the closing coil (20). The starting motor of the rotary converter is now supplied

with power, and further operations of the control equipment are dependent upon the machine running up approximately to synchronous speed. Should the machine fail to start within a period of two minutes, the master relay (3A) is de-energized by means of the "lock-out" relay (30), which is controlled by a time-limit relay (27).

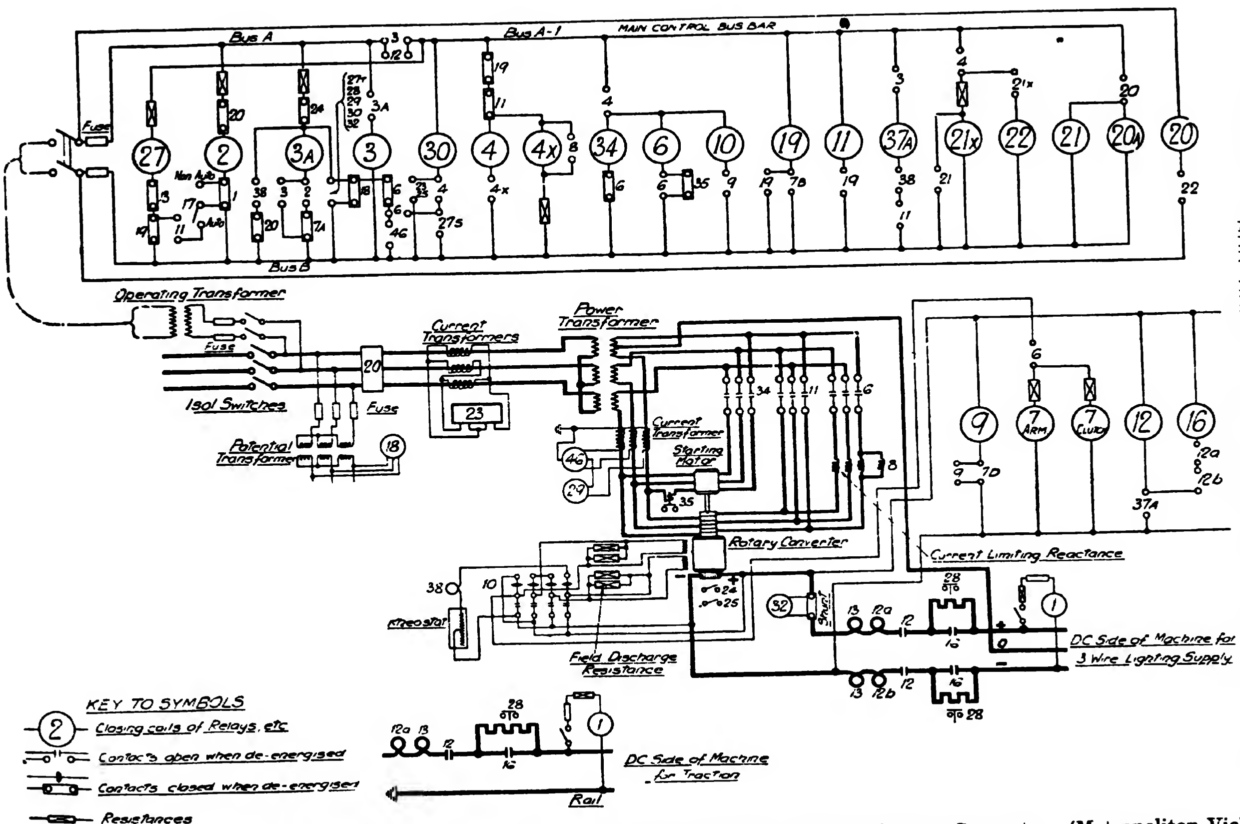
4. When the machine reaches approximately synchronous speed the decreased current in the starting-motor circuit causes the series relay (35) to close and thereby energize the synchronizing contactor (6), the closing of which connects the slip rings of the rotary converter to the transformer through current-limiting reactance coils, the starting contactor being opened by an interlock on contactor (6). The machine should then pull into synchronism, but if it fails to do so a time-limit relay (8) connected across one of the reactance coils will function and cause relay (4) to open. The starting operations will then take place a second time, and if the machine again fails to synchronize, the lock-out relay (30) will be energized via relay (27).

5. The shunt field circuit of the rotary converter is divided into two equal sections and is normally closed with these sections in series. During the period in which the synchronizing contactor (6) is closed, the armature and clutch of a polarized-motor relay (7) are energized from the direct-current brushes. When synchronism is attained and the polarity is correct the contacts (7B) of this relay will be closed, thereby closing the operating coil of auxiliary contactor (19). The closing of this contactor energizes the closing coil of the "running" contactor (11) and opens relay (4), contactor (6), and the polarized relay. An interlock on contactor (19) is connected to the time-limit relay (27), and if for any reason this contactor does not close within approximately two minutes of the commencement of the starting operations the contacts (27S) will operate and energize the lock-out relay (30).

6. If the polarity is incorrect it must be corrected by making the armature slip a pole. Thus, with incorrect polarity of the commutator voltage the contacts (7D) of the polarized relay will close and thereby energize the operating coil of auxiliary contactor (9) from the direct-current brushes. The field reversing contactor (10) will then connect the two halves of the field winding in parallel, in addition to reversing the connections. A rapid slipping of the armature occurs relatively to the revolving field produced by the alternating currents in the armature winding. When the armature has slipped through one-half of a pole pitch the commutator voltage becomes zero and, in consequence, contactor (9) opens. The field contactor (10) then returns to its normal position and the field winding is connected correctly for the machine to build up with correct polarity as the armature slips through the other half of the pole pitch. The contacts (7B) of the polarized relay will now close, thereby resulting in the closing of the "running" contactor (11).

7. The connection of the machine to the direct-current bus-bars is first made, via a load limiting rheostat, by means of contactor (12), the closing of which is dependent upon the machine having normal excitation (which is ensured by means of relay (38) connected in the field circuit, this relay controlling auxiliary contactor (37A), which controls the closing coil of contactor (12)). An auxiliary contact on contactor (12) parallels the connection—previously made by relay (3)—between the main control and auxiliary control bus-bars (*A*1, *A* respectively), and ensures that the machine cannot be disconnected from the alternating-current side until it has been disconnected from the direct-current bus-bars.

If the load is normal, the overload relay (12*a*) allows contactor (16) to close and so cut out the load limiting rheostats. This relay functions on overload, causing contactor (16) to open and cut in the load limiting rheostats, which are adjusted to limit the overload current to approximately one and a half times full-load current. Upon the removal of the overload contactor (16) is energized, and the load-limiting rheostats are short circuited. Should



KEY

1. Low voltage d.c. relay.
2. Time limit relay.
3. Auxiliary relay.
3A. Master relay.
4. Aux. contactor.
4x. Relay.
6. Synchronizing contactor.
7. Polarized relay.
8. Time limit relay.
9. Reverse field relay.
10. Field contactor.
11. Running contactor
12. Main d.c. contactor.
12A. Overload relay.
13. Underload relay.
16. D.c. contactor.
17. Master switch.
18. Reverse phase and low volt a.c. relay.
19. Aux. contactor.
20. Main oil switch.
20A. Low volt release.
21. Time limit relay.
21x. Relay.
22. Aux. contactor.
23. A.c. overload relay
24. Overspeed trip.
25. Bearing thermostat.
27. Time limit relay.
27T. Adj. time contacts of 27.
27S. 2-min. contacts of 27.
28. Thermostat.
29. Thermal time-limit relay.
30. Lock-out relay.
32. Reverse current relay.
34. Starting contactor.
35. A.c. series relay.
37A. Aux. contactor.
38. Field relay.
46. Phase balance relay.

FIG. 500.—Schematic Connection Diagram for Automatically Started Rotary Converter. (Metropolitan Vickers.)

the overload persist for any length of time and the rheostats become overheated, a thermal relay (28), mounted immediately above the rheostats, will operate and short circuit the operating coil of the master relay (3A), thereby shutting down the machine until the rheostats have cooled off to a safe value.

8. Automatic stopping—in consequence of there being no demand for power—is effected by means of an under-load relay (13) and a time-limit relay (27), the time element of which is adjustable between 3 and 20 minutes. If the underload persists, the contacts (27T) short circuit the operating coil of the master relay (3A) and the machine shuts down, relay (27) being de-energized and re-set during the process.

9. Protection against overheating due to repeated or sustained overloads is provided by a thermal relay (29) having a temperature characteristic similar to that of the machine. Operation of this relay short circuits the operating coil of the master relay (3A), and therefore the machine will be shut down temporarily until it cools off sufficiently to cause relay (29) to open. Overheating of the bearings causes the lock out relay (30) to function and the machine to shut down permanently, as this relay must be re-set by hand.

Protection against internal short circuits is provided by an induction overload relay (23) with a high setting. This relay operates the lock-out relay (30).

Protection against unbalancing of the phases is provided by relay (46), the operation of which short circuits the operating coil of the master relay (3A). Re-starting on single phase is prevented by relay (18). Should the unbalancing occur during starting the lock-out relay (30) will be energized (the operating coil of this relay being connected, by an interlock on contactor (6), to the contacts of relay (46)).

Automatic switchgear for rectifiers. On account of the simple manner in which a rectifier is started and connected to the direct-current bus-bars the switchgear for an automatic rectifier plant is much simpler than that for an automatic rotary converter plant. The main switching operations are effected automatically by oil switches and circuit breakers of the re-closing type ; the vacuum and cooling water supply are controlled automatically ; and protective devices are included to shut down the plant in the event of excessive temperature of the anodes or the failure of the water supply.

Figs. 501, 502 show elementary diagrams of the principal control circuits in connection with (1) the starting and connection of the rectifier to the direct-current bus-bars ; (2) the automatic control of the vacuum pump set. Referring to Fig. 501, automatic ignition takes place (as explained on p. 653) as soon as the main oil switch closes, and, after a short time delay, the closing coil (6) of the direct-current circuit breaker in energized by relay (5). The closing of the circuit breaker opens the closing coil and connects, via the contacts of relay (7), the low-voltage release coil to the auxiliary a.c. bus-bars. The operating coil of relay (7) is controlled by a contact-making thermometer fitted to the cover plate of the electrode chamber. Hence if the temperature rises above a predetermined value the relay opens the circuit breaker and closes an alarm circuit (*A*).

Referring to Fig. 502, the bus-bars are supplied directly from the auxiliary transformer. The master control device for the pump set is the vacuum gauge (4), which is fitted with auxiliary contacts for energizing the closing coil of the switch (9) controlling the valve of the cooling water

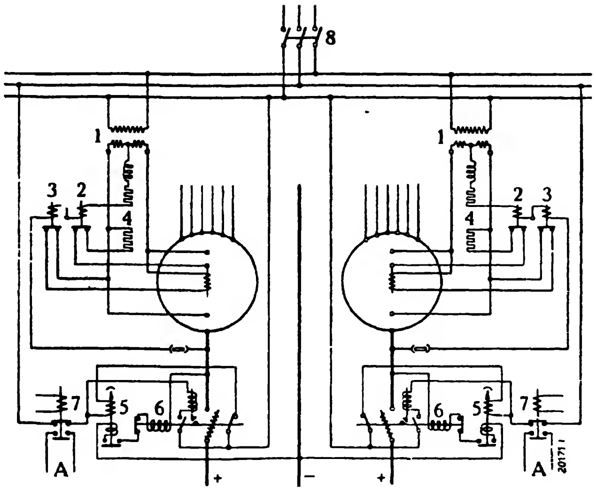


FIG. 501.—Connections for Automatic Rectifier Plant. Ignition and Connection of Rectifier to D.C. Bus-bars. (Brown-Boveri.)

1, Ignition and excitation transformer; 2, 3, relays; 4, current limiting resistance; 5, time-limit relay; 6, closing coil of d.c. circuit breaker; 7, interlocking and alarm relay; 8, auxiliary switch (operated by main oil switch) connecting auxiliary bus-bars to auxiliary transformer.

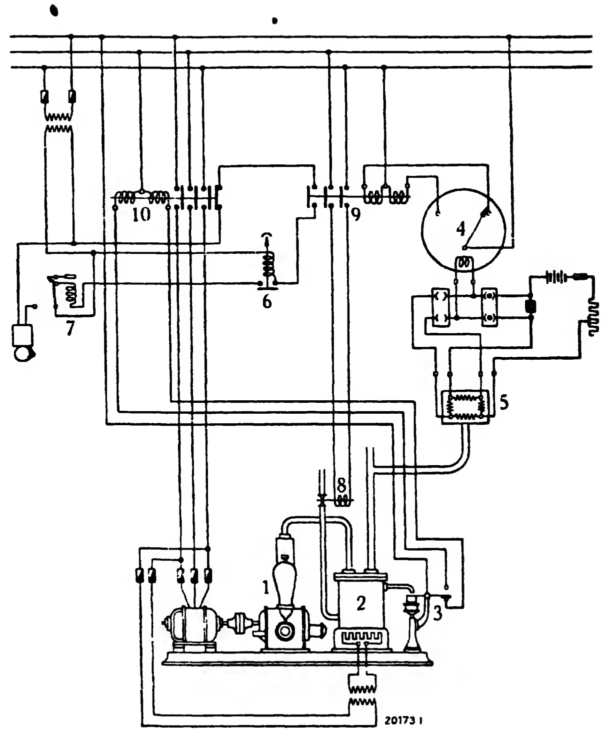


FIG. 502.—Connections for Automatic Control of Pump Set of Rectifier. (Brown-Boveri.)

1. 2, Vacuum pumps; 3, water-flow switch; 4, vacuum gauge indicator; 5 Wheatstone network of heated wires; 6, time-limit relay; 7, relay and alarm bell; 8, water valve; 9, 10, relays controlling vacuum pump set.

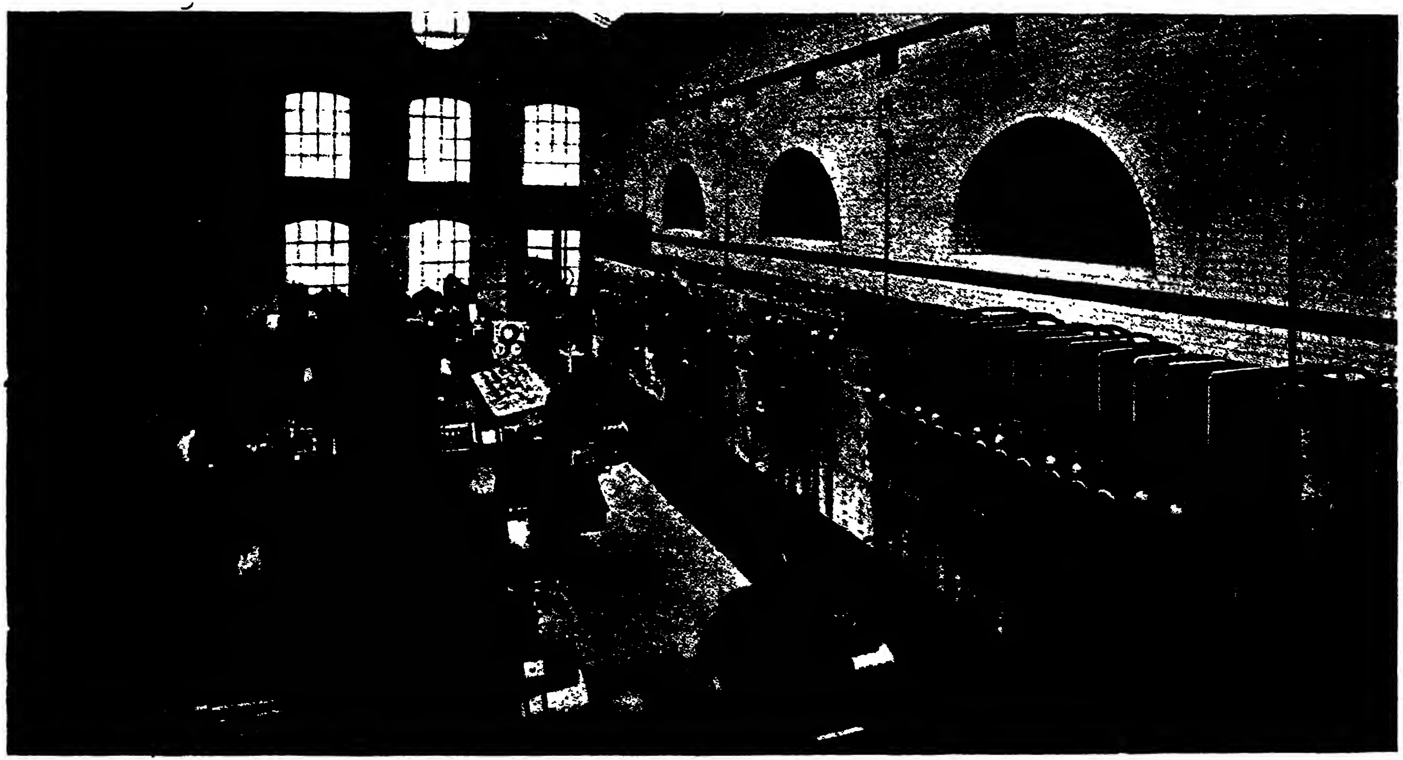


FIG. 503.—Interior of Partick Substation. (Glasgow Tramways.)

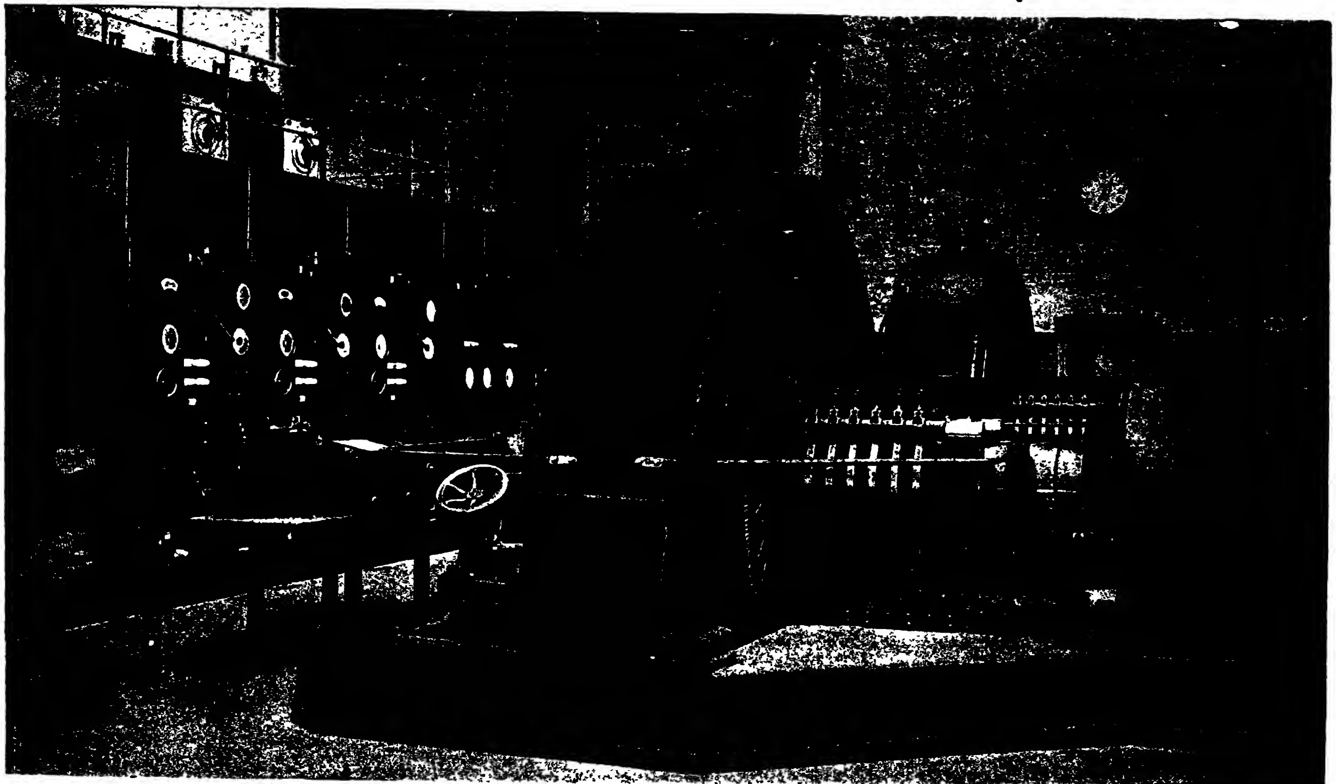


Fig. 504.—Interior of Typical Substation. (Southern Railway.) B.T.-H. Co.

supply to the mercury-vapour pump.* When the water circulation commences, the water-flow switch (3) operates and energizes the closing coil of the switch controlling the motor driving the mechanical pump. If, however, the water does not commence to circulate within a predetermined time after the closing of switch (9), an alarm and lock-out relay are energized by a time-limit relay (6).

Examples of Traction Substations

Fig. 503 illustrates a substation of the **Glasgow Tramways.** In this

Fig. 505. Arrangement of High Tension Switchgear in Typical Substation. (Southern Railway.) B.T.-H. Co.

substation the transformers and high tension alternating-current switchgear are located in an adjoining room, the oil-switches being electrically controlled from a desk type control board located in the centre of the substation. Each of the rotary converters is provided with a starting motor and a negative booster.

The direct-current switch panels occupy the right-hand portion of the switchboard. In the foreground are five panels controlling fifteen line (positive) feeders. The lower contacts of the switches are connected to vertical plug-bars on the sub-panels, each of which has four holes for

* This arrangement is employed when the cooling water is obtained from supply mains.

the insertion of a plug. The corresponding (four) horizontal bars are mounted on the back of the panels, and each is connected through a switch to one end of the field winding of a corresponding booster, the other ends of the field windings being connected to the positive bus-bar through suitable switches. The upper contacts of the feeder switches are

FIG. 596. -Unattended Substation on London Underground Railways. (Metropolitan-Vickers.)

[NOTE. -On the left are the air-blast transformers and starting panels. The main switchboard is on the right, and the load limiting resistances are mounted above the " machine " panels.]

connected directly to the positive bus-bar. Thus any feeder, or a group of feeders, may be connected so as to excite any booster.

The switches controlling the boosters are adjacent to the feeder panels. The upper row of switches control the field windings. The lower row of switches control the armatures, one switch of each group connecting the positive brush to the negative bus-bar, and the other switch connecting the negative brush to the vertical plug-bar on the sub-panel. The horizontal plug-bars extend along the back of the board to the track-feeder panels. which are located at the far end of the board, adjacent to the testing panel. Each track feeder is connected, through a switch and an ammeter, to a vertical plug-bar, so that any track feeder may be

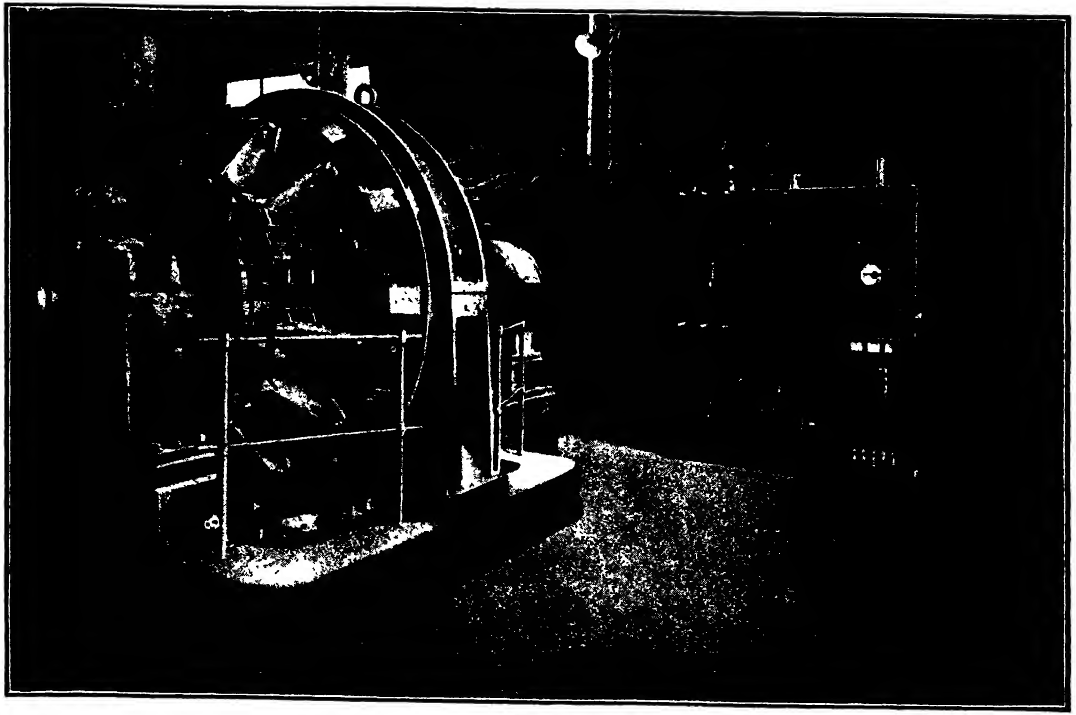


Fig. 507 —Unattended substation on London Underground Railways. View showing d.c. Side (Flash Barriers) of Rotary converter, starting panels, and air-blast transformers. (Metropolitan-Vickers.)

connected to any booster. Between the booster panels and the track-feeder panels are located the panels controlling the direct-current sides of the rotary converters, these panels being distinguished by the field rheostats on the sub-panels.

Fig. 504 illustrates a typical substation of the **Southern Railway.** The rotary converters are six-phase compound wound machines, rated at 1500 kW., 600/630 volts, 300 r.p.m., 25 cycles. Each machine is

FIG. 508.—Three 1000 kW., 1500-Volt Rectifier Sets in Unattended Substation of Dutch Railways. (Brown-Boveri.)

supplied through three single-phase, high reactance, oil-cooled transformers, which are located on the floor adjacent to the machines. The low-tension connections on both sides consist of bare copper strip.

The switchboard controlling the rotary converters is also shown in Fig. 504. As the machines are of the induction-motor started, self-synchronizing type, the alternating-current switchgear consists of (1) remote controlled oil-switches for the high-tension side of the transformers ; (2) short-circuiting switches for the starting motors. The short-circuiting switches are mounted on the bedplates near the appropriate starting motors, and the levers for operating the oil-switches are mounted on the switchboard. The instruments on each machine panel comprise a main direct-current ammeter, a field ammeter, an alternating-current ammeter, and a power-factor meter.

The oil-switches controlling the transformers, together with those

FIG. 509.—Brown-Boveri 1200 kW., 800-Volt Rectifiers in Substation of Berlin Suburban Railways.

controlling the high-tension feeders, are located in compartments of moulded stone arranged on a gallery, as shown in Fig. 505. In this illustration the bus-bar compartments are also shown.

Views of an unattended substation of the **London Underground Railways** are shown in Figs. 506, 507. This substation contains three 1500 kW.

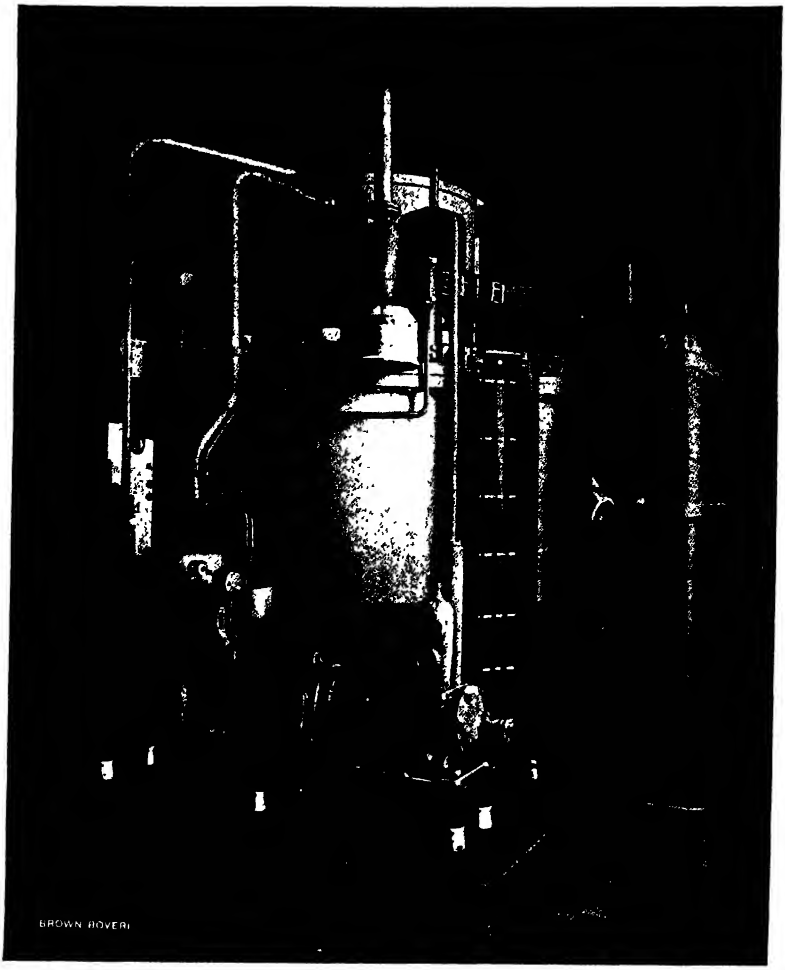


Fig. 510.—Brown-Boveri 4000 kW., 1500-Volt Rectifier in Substation of Czechoslovakian State Railways, Prague.

rotary converters and is arranged for supervisory control from an attended substation about three miles distant. Each rotary converter is supplied from three single-phase, shell type, air-blast transformers with double secondary windings connected double delta.

The initial impulses causing the starting or stopping of the plant are given, through pilot wires, from the attended substation, e.g. by pressing

push buttons any of the high-tension oil switches, or any of the direct-current feeder circuit breakers may be opened or closed, or any of the rotary converters may be started or stopped. Signal lamps on the supervisory control panel indicate the positions of the main switches and feeder circuit breakers as well as the condition of the rotary converters. Moreover, in the event of a shut down, indication is given whether this is temporary or permanent (i.e. a lock out).

Examples of rectifier substations are shown in Figs. 508, 509, the former being representative of the substations of the **Dutch main-line railways** and the latter being representative of the substations of the **Berlin suburban railways.** In both cases all the substations are equipped with rectifiers, there being seven substations having an aggregate output of 21,000 kW. in the former case, and forty substations having an aggregate output of 118,000 kW. in the latter case.

The substation shown in Fig. 508 is arranged for supervisory control and is equipped with three 1000 kW. rectifier sets. Each set consists of two 500 kW., 1500-volt, 6-anode rectifiers operating in parallel, and is supplied from a three-phase 1330 kVA. transformer with double six-phase, star-connected, secondary windings, the " absorption coil " (which is rated at 250 kVA., 150 cycles) being connected between the two neutral points. Each set has a common vacuum pump and a self-contained water cooling plant working on the closed circuit principle (Fig. 490). The transformers and absorption coils are of the self-cooled, oil-immersed type, and are located in cubicles, each of which is provided with a ventilating shaft 6 metres (21 ft.) high to ensure adequate natural circulation of air around the transformer in hot weather.

Fig. 510 shows a large (400 kW.) rectifier installed in a substation of the **Czechoslovakian railways.** This rectifier has twelve anodes and duplicate vacuum pumps.

APPENDIX I

REGULATIONS* MADE BY THE MINISTER OF TRANSPORT UNDER THE PROVISIONS OF SPECIAL TRAMWAYS AND RAILLESS TRACTION ACTS OR LIGHT RAILWAY ORDERS; FOR REGULATING THE USE OF ELECTRICAL POWER; FOR PREVENTING FUSION OR INJURIOUS ELECTROLYTIC ACTION OF OR ON GAS OR WATER PIPES OR OTHER METALLIC PIPES, STRUCTURES, OR SUBSTANCES; AND FOR MINIMIZING AS FAR AS IS REASONABLY PRACTICABLE INJURIOUS INTERFERENCE WITH THE ELECTRIC WIRES, LINES, AND APPARATUS OF PARTIES OTHER THAN THE COMPANY, AND THE CURRENTS THEREIN, WHETHER SUCH LINES DO OR DO NOT USE THE EARTH AS A RETURN.

First made, March, 1894. Revised, April, 1903.
Further revised, September, 1928.

Definitions

In the following regulations—

The expression "energy" means electrical energy; "generator," the dynamo or dynamos or other electrical apparatus used for the generation or conversion of energy; "motor," any electric motor carried on a car and used for the conversion of energy; "pipe," any gas or water pipe or other metallic pipe, structure, or substance; "wire," any wire or apparatus used for telegraphic, telephonic, electrical signalling, or other similar purposes; "current," an electric current exceeding one-thousandth part of one ampere.

The expression "the Company" has the same meaning as in the Tramways and Railless Traction Acts [Light Railways Order].

Regulations

1. Any generator shall be of such pattern and construction as to be capable of producing a continuous current without appreciable pulsation.†

2. (T.) *One of the two conductors used for transmitting energy from the generator to the motors shall be in every case insulated from earth, and is hereinafter referred to as the "line"; the other may be insulated throughout, or may be uninsulated in such parts and to such extent as is provided in the following regulations, and is hereinafter referred to as the "return."*

(R.) *The positive and negative conductors used for transmitting energy from the generator to the motors shall be insulated from earth.*

3. (T.) *Where any rails on which cars run or any conductors laid between or within three feet of such rails form any part of a return, such part may be uninsulated. All other returns or parts of a return shall be insulated, unless of such sectional area as will reduce the difference of potential between the ends of the uninsulated portion of the return below the limit laid down in Regulation 7.*

4. (T.) *When any uninsulated conductor laid between or within three feet of*

* Separate regulations are issued for tramways and railless routes, but they are here shown combined for convenience. The regulations which are common to both tramways and railless routes are shown in Roman type; those which apply only to one system or the other are shown in italic, the letter T or R, combined with the number of the regulation indicating whether the regulation applies to tramways (T) or railless routes (R).

† The Minister of Transport will be prepared to consider the issue of regulations for the use of alternating currents for electrical traction on application.

the rails forms any part of a return, it shall be electrically connected to the rails at distances apart not exceeding 100 feet by means of copper strips having a sectional area of at least one-sixteenth of a square inch, or by other means of equal conductivity.

5. (T.) (a) *When any part of a return is uninsulated it shall be connected with the negative terminal of the generator, and in such case the negative terminal of the generator shall also be directly connected, through the current-indicator hereinafter mentioned, to two separate earth connections which shall be placed not less than 20 yards apart.*

(b) *The earth connections referred to in this regulation shall be constructed, laid, and maintained so as to secure electrical contact with the general mass of earth, and so that, if possible, an E.M.F., not exceeding four volts, shall suffice to produce a current of at least two amperes from one earth connection to the other through the earth, and a test shall be made once in every month to ascertain whether this requirement is complied with.*

(c) *Provided that in place of such two earth connections the Company may make one connection to a main for water supply of not less than three inches internal diameter, with the consent of the owner thereof and of the person supplying the water, and provided that where, from the nature of the soil or for other reasons, the Company can show to the satisfaction of the Minister of Transport that the earth connections herein specified cannot be constructed and maintained without undue expense, the provisions of this regulation shall not apply.*

(d) *No portion of either earth connection shall be placed within six feet of any pipe except a main for water supply of not less than three inches internal diameter which is metallically connected to the earth connections with the consents hereinbefore specified.*

(e) *When the generator is at a considerable distance from the tramway the uninsulated return shall be connected to the negative terminal of the generator by means of one or more insulated return conductors, and the generator shall have no other connection with earth ; and in such case the end of each insulated return connected with the uninsulated return shall be connected also through a current indicator to two separate earth connections, or with the necessary consents to a main for water supply, or with the like consents to both in the manner prescribed in this regulation.*

(f) *The current indicator may consist of an indicator at the generating station connected by insulated wires to the terminals of a resistance interposed between the return and the earth connection or connections, or it may consist of a suitable low-resistance maximum demand indicator. The said resistance, or the resistance of the maximum demand indicator, shall be such that the maximum current laid down in Regulation 6 (i) shall produce a difference of potential not exceeding one volt between the terminals. The indicator shall be so constructed as to indicate correctly the current passing through the resistance when connected to the terminals by the insulated wires before-mentioned.*

6. (T.) *When the return is partly or entirely uninsulated the Company shall in the construction and maintenance of the tramway* (a) *so separate the uninsulated return from the general mass of earth, and from any pipe in the vicinity ;* (b) *so connect together the several lengths of the rails ;* (c) *adopt such means for reducing the difference, produced by the current, between the potential of the uninsulated return at any one point and the potential of the uninsulated return at any other point ; and* (d) *so maintain the efficiency of the earth connections specified in the preceding regulations as to fulfil the following conditions, viz. -*

(i) *That the current passing from the earth connections through the indicator to the generator or through the resistance to the insulated return shall not at any time exceed either two amperes per mile of single tramway line or five per cent of the total current output of the station.*

(ii) *That if at any time and at any place a test be made by connecting a galvanometer or other current-indicator to the uninsulated return and to any pipe in the vicinity, it shall always be possible to reverse the direction of any current indicated by interposing a battery of three Leclanché cells connected in series if the direction of the current is from the return to the pipe, or by interposing one Leclanché cell if the direction of the current is from the pipe to the return.*

The owner of any such pipe may require the Company to permit him at reasonable times and intervals to ascertain by test that the conditions specified in (ii) *are complied with as regards his pipe.*

7. (T.) *When the return is partly or entirely uninsulated a continuous record shall be kept by the Company of the difference of potential during the working of the tramway between points on the uninsulated return. If at any time such difference of potential between any two points exceeds the limit of seven volts, the Company shall take immediate steps to reduce it below that limit.*

8. (T.) *Every electrical connection with any pipe shall be so arranged as to admit of easy examination, and shall be tested by the Company at least once in every three months.*

9. (T), 3 (R). The insulation of the line, *and of the return when insulated,* and of all feeders and other conductors, shall be so maintained that the leakage current shall not exceed one hundredth of an ampere per mile of tramway. The leakage current shall be ascertained not less frequently than once in every week before or after the hours of running when the line is fully charged. If at any time it should be found that the leakage current exceeds one-half of an ampere per mile of route the leak shall be localized and removed as soon as practicable, and the running of the *cars and trolley vehicles* shall be stopped unless the leak is localized and removed within 24 hours. *Provided that where both line and return are placed within a conduit this regulation shall not apply.*

10. (T.) *Any insulated return shall be placed parallel to and at a distance not exceeding three feet from the line when the line and return are both erected overhead, or eighteen inches when they are both laid underground.*

11. (T), 4 (R). In the disposition, connections, and working of feeders, the Company shall take all reasonable precautions to avoid injurious interference with any existing wires.

12. (T), 5 (R). The Company shall so construct and maintain their system as to secure good contact between the motors and the line *and return respectively.*

13. (T), 6 (R). The Company shall adopt the best means available to prevent the occurrence of undue sparking at the rubbing or rolling contacts in any place and in the construction and use of their generator and motors.

14. (T.) *Where the line or return or both are laid in a conduit the following conditions shall be complied with in the construction and maintenance of such conduit—*

(a) *The conduit shall be so constructed as to admit of examination of and access to the conductors contained therein and their insulators and supports.*

(b) *It shall be so constructed as to be readily cleared of accumulation of dust or other débris, and no such accumulation shall be permitted to remain.*

(c) *It shall be laid to such falls and so connected to sumps or other means of drainage, as to automatically clear itself of water without danger of the water reaching the level of the conductors.*

(d) *If the conduit is formed of metal, all separate lengths shall be so jointed as to secure efficient metallic continuity for the passage of electric*

currents. Where the rails are used to form any part of the return they shall be electrically connected to the conduit by means of copper strips having a sectional area of at least one-sixteenth of an inch, or other means of equal conductivity, at distances apart not exceeding 100 *feet. Where the return is wholly insulated and contained within the conduit, the latter shall be connected to earth at the generating station or sub-station through a high-resistance galvanometer suitable for the indication of any contact or partial contact of either the line or the return with the conduit.*

(e) *If the conduit is formed of any non-metallic material not being of high insulating quality and impervious to moisture throughout, the conductors shall be carried on insulators, the supports for which shall be in metallic contact with one another throughout.*

(f) *The negative conductor shall be connected with earth at the station by a voltmeter, and may also be connected with earth at the generating station or sub-station by an adjustable resistance and current indicator. Neither conductor shall otherwise be permanently connected with earth.*

(g) *The conductors shall be constructed in sections not exceeding one-half a mile in length, and in the event of a leak occurring on either conductor that conductor shall at once be connected with the negative pole of the dynamo, and shall remain so connected until the leak can be removed.*

(h) *The leakage current shall be ascertained daily, before or after the hours of running, when the line is fully charged, and if at any time it shall be found to exceed one ampere per mile of tramway the leak shall be localized and removed as soon as practicable, and the running of the cars shall be stopped unless the leak is localized and removed within* 24 *hours.*

15. (T), 7 (R). The Company shall, so far as may be applicable to their system of working, keep records as specified below. These records shall, if and when required, be forwarded for the information of the Minister of Transport.

Number of *cars* or *trolley vehicles* running.

Number of miles of single tramway line, or *length of routes*.

Daily Records

Maximum working current.

Maximum working pressure.

(T.) *Maximum current from the earth plates or water-pipe connections* (vide *Regulation* 6 (i) *where the indicator is at the generating works.*

(T.) *Fall of potential in return* (vide *Regulation* 7).

(T.) Leakage current (vide Regulation 14 (*h*)).

Weekly Records

Leakage current (vide Regulation 9 (T) *or* 3 (R)).

(T.) *Maximum current from the earth plates or water-pipe connections* (vide *Regulation* 6 (i)) *where a maximum demand indicator is used.*

Monthly Records

(T.) *Condition of earth connections* (vide *Regulation* 5).

Quarterly Records

(T.) *Conductance of joints to pipes* (vide *Regulation* 8).

Occasional Records

(T.) *Specimens of tests made under provisions of Regulation* 6 (ii).

(R.) *Localization and removal of leakage, stating time required.*

(R.) *Particulars of any abnormal occurrence affecting the electric working of the routes.*

MEMORANDUM AND REGULATIONS REGARDING DETAILS OF CONSTRUCTION OF NEW LINES AND EQUIPMENT

(NOTE.—These requirements and recommendations apply also to reconstruction of track, cars and equipment undertaken after the date of the Memorandum, as well as to new lines or new stock.)

The paragraphs in *italics* are typical working Regulations made by the Minister of Transport after the systems have been inspected and authorized for passenger working.

I.—CONSTRUCTIONAL DETAILS

(a) *Clearance*

1. There must under all conditions be at least 15 in. clear between any point on the sides of passing cars, and also a similar space between any point on the side of a car and any standing work whether on straight or curved tracks.

For new and reconstructed standard gauge systems, double track on the straight should be laid with a standard interval between centres of 8 ft. 6 in., with a corresponding increase on curves, to permit of through running and the use of wide cars.

2. Side posts to be placed inside the kerb at a sufficient distance from it to prevent the possibility of road vehicles coming into contact with them.

3. There must be at least 15 in. between any point on the side of a car and the kerb, whether on straight or curved tracks, unless otherwise approved by the Minister of Transport.

In roads where the general vehicular traffic is considerable, and the full interval of 9 ft. 6 in. between the edge of the kerb and the nearest rail cannot be provided by a widening of the metalled roadway, it is desirable to avoid as far as possible such an interval between rail and kerb—for example, from 5 ft. to 7 ft.—as might lead to the liability of other vehicles being trapped. In such cases it will be for consideration, having regard to the available width of roadway, whether the single or double line should not be laid so far out of centre of the road as to provide the minimum clearance between car and kerb, as specified above, on the one side, and the maximum possible clearance on the other.

4. The clearance between the top deck of uncovered cars and the underside of bridges should not, if possible, be less than 6 ft. 6 in. Where this clearance cannot be obtained special precautions in working will be required, and each case will be considered on its merits.

(b) *Overhead Electrical Equipment*

1. *The electrical pressure between the overhead conductors used in connection with the working of the tramways and the earth, or between the two overhead conductors used in connection with the working of the trolley-vehicle routes, or between any two such conductors, shall in no case exceed* 600 *volts. The electrical energy supplied through feeders shall not be generated at, or transformed to, a pressure higher than* 650 *volts, except with the written consent of the Minister of Transport and subject to such regulations and conditions as he may prescribe.*

2. Centre posts must not be used without the consent, in every case, of the Minister of Transport.

3. The stone-kerbing round isolated centre or span wire posts should not be such as to enable any person to stand upon it as a refuge, unless the clearance is ample for safety.

4. Span wire construction is preferred so as to provide for trolley wires being centrally spaced over their respective tracks. Bracket arms, not as a rule exceeding 16 ft. in length, may, however, be used if this form of construction is economically desirable.

5. *The interval between the supports to which the overhead conductors used in connection with the working of the tramways are attached shall not, except with the approval of the Minister of Transport, exceed 120 ft., and as a general rule the overhead conductors shall in no part be at a less height than 20 ft. from the surface of the street, except where they pass under bridges.*

6. *Each positive conductor shall be divided up into sections not exceeding (except with the special approval of the Minister of Transport) one-half of a mile in length, between every two of which shall be inserted an emergency switch so enclosed as to be inaccessible to pedestrians.*

7. *The poles carrying section switch boxes shall be efficiently connected with earth.*

8. *Where on trolley-vehicle routes there are two negative trolley wires, these shall be cross-connected at intervals of not more than half a mile.*

9. *No gas or electric lamp bracket shall be attached to any pole unless either triple insulation is provided between the pole and the overhead conductors or the pole is bonded to the tramway rails.*

In the case of any lamp suspended from the span wire carrying the overhead tramway conductors that portion of the span wire from which the lamp is suspended shall be separated from that portion or portions on which the trolley wire or wires are carried by a suitable insulator.

10. *Each separate insulator on the overhead conductors shall be tested not less frequently than once in a month, and any insulator found to be defective shall at once be removed and an efficient insulator substituted.*

If and whenever telegraph, telephone, or other wires, unprotected with a permanent insulating covering, cross above, or are liable to fall upon, or to be blown on to, the overhead conductors of the tramway or trolley-vehicle routes, efficient guard wires shall be erected and maintained at all such places.

Provided that this regulation shall not apply to Post Office over-road stay wires or other uncovered wires which are not electrical conductors where they are connected at each end to the tramway rails or negative conductor.

The guard wires shall be connected to the negative overhead conductor (on trolley-vehicle routes) at intervals of not more than five spans.

NOTE.—Guard Wire Regulations are given on p. 692.

(c) *Permanent Way*

1. The weight of rails, on public roads, should not be less than 90 lb. per yard, and one or other of the British Standard sections for Tramway Rails is preferred.

2. The groove of new rails must not exceed $1\frac{1}{8}$ in. in width, but a groove not exceeding $1\frac{1}{4}$ in. will be accepted on curves of less than 150 ft. radius, and for special work.

3. The removal of storm water accumulating in the rail groove to be adequately provided for by slotted rails, or other approved device, suitably connected to the drainage system. The number of " draw-off " points to be increased on gradients or at termini.

4. The details of permanent way and mode of construction in the case of new lines should be submitted to the Minister of Transport for approval before work is commenced, and may not be substantially varied at any time without the Minister's consent.

II. Car Equipment

1. Type drawings of all cars intended to be used on a line must be submitted to the Minister of Transport for approval, before orders for the cars are placed (see paragraph 15 below).

2. *Every motor carriage used on the tramways shall comply with the following requirements, that is to say—*

(a) *It shall be fitted, if and when required by the Minister of Transport, with an apparatus to indicate to the driver the speed at which it is running.*

Instructional cars should preferably be so fitted.

(b) *Its wheels shall be equipped with brake-blocks, which can be applied by a screw or by other means, and there shall be in addition an adequate electric brake.*

Note.—Where for a considerable distance the gradients are 1 in 15 or steeper, the following will be added to this regulation —

"*and a track brake approved by the Minister of Transport for use on the tramways.*"

An electric brake will not be accepted as "adequate" unless it can be applied by a step by step movement either of a separate brake handle, or of the controller handle only, in the opposite direction to that necessary to apply power.

(c) *It shall be conspicuously numbered inside and outside.*

(d) *It shall be fitted with a suitable life-guard, and with a special bell to be sounded as a warning when necessary.*

Life-guards must be of the falling tray type, and the following constructional features observed—

(i) A rapid action type of release to be used.

(ii) The bottom edge of the hanging front gate to be as close to the ground as practicable, and this gate should be free to move backwards through an angle as near to 90° as possible.

(iii) There should be at least 3 ft. 6 in. between the front gate and the leading edge of the tray.

(iv) The tray to have a minimum clear depth from front to back of 2 ft.

(v) Both gate and tray should be at least as wide as the outside of the frame of the truck.

(vi) A vertical back or barrier at least 12 in. high to be provided behind the tray.

(vii) The whole of the space bounded by the gate, sides and back of the tray to be kept clear as far as possible of any obstruction below the level of the bottom of the main frame.

(viii) A side guard, preferably of the collapsible type, working in conjunction with the tray, to be fitted on the near side. Where folding steps are in use, it is desirable that a similar side guard should also be provided on the off-side.

(ix) The actuating spring of the tray should be so designed that a pull of at least 50 lb. on the front edge of the tray shall be necessary to lift the tray from its actuated position.

(e) *It shall be so constructed as to enable the driver to command the fullest possible view of the road.*

Staircases of the "reversed" type must not be adopted in future.

2 (R). *Every trolley vehicle used on the routes shall comply with the following requirements, that is to say—*

(a) *It shall be fitted, if and when required by the Minister of Transport, with an apparatus to indicate to the driver the speed at which it is running.*

(b) *It shall be fitted with at least two independent brakes each capable of*

stopping and holding the vehicle on any gradient on the routes. One of the brakes at least must be applied by pedal.

(c) *It shall be conspicuously numbered inside and outside.*

(d) *It shall be fitted with a bell, horn, gong, or other approved means of giving warning when necessary.*

(e) *It shall be so constructed as to enable the driver to command the fullest possible view of the road.*

3. It is desirable that all new cars should be equipped with folding steps. In the case of new cars designed for exit (or entrance) at the leading end on the near side, the steps used for the purpose must be of the folding type, and a door or collapsible gate provided. Arrangements will be necessary to ensure that, before the car is put in motion, the step is folded, and the door or gate closed; also that the step is lowered when the door or gate is opened. A vertical clearance of at least 1 ft. 2 in. between the lowest part of the step or its equipment when folded and the rail table to be provided. If any exception is desired to the provisions of this paragraph, the circumstances must be explained in detail so that the case may receive due consideration.

4. On lines having severe gradients and sharp curves, the use of double-deck cars may be objected to.

5. Where the gauge of the line is 3 ft. 6 in. or less, top deck covers must not be used, except for routes upon which their use has already been approved.

6. Arrangements for sanding each rail to be provided at each end of the cars. On systems having severe or dangerous gradients arrangements to enable the motorman to sand the rail behind as well as in front of the car may be required.

7. Top deck railings should be at least 3 ft. 6 in. high.

8. *All railings shall be connected with earth, except that those used by passengers in mounting or alighting from a carriage may be insulated if so desired.*

9. *The hand-rails used by passengers on entering or leaving a trolley vehicle shall either be constructed of some non-conducting substance or be covered with a suitable insulating material.*

10. *All electrical conductors fixed upon the carriages and trolley vehicles in connection with the trolley wheels shall be formed of flexible cables protected by indiarubber insulation of the highest quality, and additionally protected wherever they are adjacent to any metal so as to avoid risk of the metal becoming charged.*

11. *The insulation of the electrical conductors from the metal work of each trolley vehicle shall be tested and recorded daily before the vehicle is used for passenger traffic with a testing pressure not less than 500 volts. No trolley vehicle shall be taken out for use if the leakage current exceeds 3 milliamperes,*

12. *The trolley standard of every double-deck carriage shall be electrically connected to the wheels of the carriage in such manner as either to prevent the possibility of the standard becoming electrically charged from any defect in the conductors contained within it or in the event of the standard becoming electrically charged to give a distinctive and continuous warning signal, recognizable both by day and by night to the driver or conductor. No passenger shall be allowed to travel on the upper deck of a carriage as long as there is risk of electric shock.*

NOTE.—This regulation will not apply to the trolley base on the top cover of double-deck cars.

(13) *An emergency cut-off switch shall be provided and fixed so as to be conveniently reached by the driver in case of any failure of action of the controller switch.*

14. Where trolley ropes cannot be dispensed with or tied up, precautions must be taken to prevent the " slack " causing accidents.

15. Trolley booms and heads should be so designed and secured as to minimize danger arising from the following causes—

(a) Dewiring of trolley heads.

(*b*) Dewired trolley heads catching up in any part of the overhead equipment or guardwiring.
(*c*) Pulling out or breakage of trolley boom or standard.
(*d*) Swinging of trolley boom after trolley head is dewired.
(*e*) Falling of detached trolley head.

The use of non-fouling trolley heads, or slipper collectors, and some frictional or other device to check vertical movement or lateral swing of a trolley boom in the event of dewiring, is for consideration. It may also be desirable to use a detachable head secured by a rope to the boom.

16. In cases where the use of trailer-cars is approved the trailer draw-gear shall, with a view to securing interchangeability, be constructed of such height and standard dimensions as may be required by the Minister of Transport.

17. Alterations which conflict with the above requirements, etc., to cars of approved design are not permissible, nor should a new contract be made nor a new programme of manufacture be commenced until approval has been given of the design and general equipment.

III. General

No trailer carriage shall be used on the tramways without the consent of the Minister of Transport except—

(a) *In the case of the removal of a disabled carriage.*
(b) *For the conveyance of salt, sand, and other materials or stores for the purposes of the tramways undertaking.*

When trailer carriages are used for the conveyance of salt, etc., under (b) *the following requirements shall be complied with—*

(1) *More than one trailer carriage shall not be attached to any motor carriage.*
(2) *No passengers shall be carried in any motor carriage to which a trailer carriage is attached.*
(3) *The trailer carriage shall be fitted with efficient brakes and there shall be a man on the trailer carriage to attend to the brakes.*

When trailer carriages are used with the consent of the Minister of Transport for the conveyance of passengers, the following requirements shall be complied with —

(a) *The wheels of the trailer carriages shall be fitted with brake blocks, which can be applied by a screw or by other means.*
(b) *The carriages shall be conspicuously numbered inside and outside.*
(c) *Not more than two carriages shall be coupled together. Where two are so running there shall be, in all cases where the brakes on the second carriage are not controlled from the first carriage, a man on the front platform of the second carriage, in addition to the conductor, whose sole duty it shall be to attend to the brakes, means being provided by which the driver can signal to this man when he wishes the brakes on the rear carriage to be applied.*

No trailer vehicle shall be used on the routes except in the case of the removal of a disabled trolley vehicle.

Every carriage used on the tramways for the conveyance of passengers shall be so constructed as to provide for the safety of passengers, and for their safe entrance to, exit from, and accommodation in such carriage.

Carriages from which passengers are allowed to alight on the near side at the front or driver's end shall be distinguished by the exhibition of a conspicuous notice on the near side of the dash at each end in red lettering on a white plaque bearing the words " Front exit car."

Provided that in the case of the use of trailer carriages such notices shall be exhibited on the leading end of the front carriage and the rear end of the rear carriage.

No passenger shall be allowed to travel standing on the platforms, staircases, or upper deck of a carriage.

No passenger shall be allowed to travel standing on the steps, platform, staircase, or upper deck of a trolley vehicle.

During the period between one hour after sunset and one hour before sunrise or during fog every carriage on the tramways, or where two carriages are coupled together the front carriage, shall carry a lamp so constructed and placed as to exhibit a white light visible within a reasonable distance to the front and every carriage, or where two carriages are coupled together the rear carriage, shall carry a lamp so constructed and placed as to exhibit a red light visible within a reasonable distance to the rear.

During the hours of darkness, which expression means in summer time the time between one hour after sunset and one hour before sunrise and during the remainder of the year the time between half-an-hour after sunset and half-an-hour before sunrise, and at any time during fog, every trolley vehicle on the routes shall carry a lamp on each side so constructed and placed as to exhibit white lights visible within a reasonable distance to the front, and every such vehicle shall carry a lamp so constructed and placed as to exhibit a red light visible within a reasonable distance to the rear. The front lamps shall be fixed on opposite sides of the vehicle, be as nearly as possible of the same power, and be fixed at the same height from the ground in such position that no part of the vehicle or its equivalent extends laterally on the same side as the lamp more than 12 in. beyond the centre of the lamp. The rear lamp shall be fixed either on the centre line or on the off-side of the vehicle.

GUARD WIRES ON ELECTRIC TRAMWAYS AND LIGHT RAILWAYS (LAID ON PUBLIC ROADS) AND TROLLEY-VEHICLE ROUTES

Explanatory Memorandum

Note.—The expression "telegraph wire" in this memorandum includes all telegraph, telephone, and other wires referred to in the Regulation (p. 688).

For the purpose of this memorandum, telegraph wires are divided into two classes, namely—

(*a*) Wires weighing less than 100 lb. per mile (No. 14, S.W.G.).

(*b*) Wires weighing 100 lb. per mile (No. 14, S.W.G.) or more.

On *trolley-vehicle routes* the requirements are based upon the connection of the negative trolley wire to earth or to the rails of a tramway, as will be required by Regulation in all cases. Each guard wire on these routes shall be electrically continuous and well connected to the negative trolley wire at each end span and at intervals of not more than five spans. The negative trolley wire need not be guarded.

On *tramways* each guard wire should be well earthed at each end, and at intervals of not more than five spans. The resistance to earth should be sufficiently low to insure that a telegraph wire falling on and making contact with the guard wire and trolley wire at any time will cause the circuit-breaker protecting that section to open.

The earth connection should be made by connecting the guard wire to the rails by means of a copper bond. When first erected, the resistance to earth of the guard wires should be tested, and periodical tests should be made to prove that the earth connection is efficient.

Guard wires should be, in general, of galvanized steel, but in manufacturing districts, in which such wires are liable to corrosion, bronze or hard-drawn copper wires should be used.

The gauge of the guard wire should not be less than seven strands of No. 16 or one of No. 8 wire.

The supports for the guard wires should be rigid and of sufficient strength for their purpose, and at each support each guard wire should be *either* (*on*

trolley-vehicle routes) insulated from the support, *or* (*on tramways*) securely bound in or terminated.

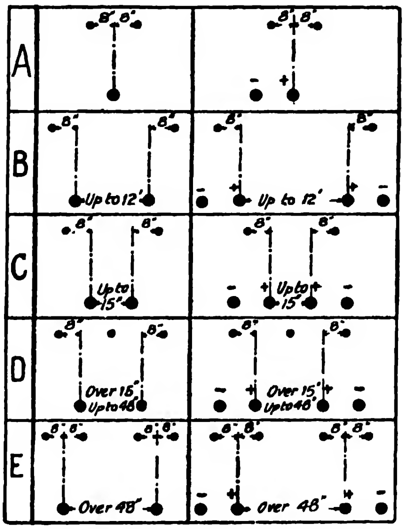
The rise of the trolley boom should be so limited that if the trolley leaves the wire it will not foul the guard wires.

Telegraph Wires Crossing Trolley Wires

Class (a).—Wires Weighing less than 100 *lb. per Mile*

1. Where there is one positive trolley wire, two guard wires should be erected (see Fig. A).

2. Where there are two positive trolley wires at a distance not exceeding 12 ft. apart, two guard wires should be erected (see Fig. B).



Overhead Trolley Tramways. Trackless (Railless) Trolley Routes.

3. In special cases, at junctions or curves, where parallel guard wiring would be complicated, two guard wires only will generally suffice if so erected that a falling wire must fall on them before it can fall on the trolley wire.

Class (b).—Wires weighing 100 *lb. or more per Mile*

4. Where there is only one positive trolley wire, two guard wires should be erected (see Fig. A).

5. Where there are two positive trolley wires not more than 15 in. apart, two guard wires should be erected (see Fig. C).

6. Where there are two positive trolley wires and the distance between them exceeds 15 in., but does not exceed 48 in., three guard wires should be erected (see Fig. D).

7. Where the distance between the two positive trolley wires exceeds 48 in., each trolley wire should be separately guarded (see Fig. E).

8. It is desirable, where possible, to divert telegraph wires from above trolley junctions and trolley-wire crossings, and undertakers should endeavour to make arrangements to that effect with the owners of telegraph wires.

Telegraph Wires Parallel to Trolley Wires

9. Where telegraph wires not crossing a trolley wire are liable to fall upon or to be blown on to a trolley wire, a guard wire should be so erected that a falling wire must fall on the guard wire before it can fall on the trolley wire.

If the trolley wire is within the angle formed by the vertical plane of a telegraph wire, and an imaginary plane drawn at an angle of 45° from the uppermost telegraph wire on the side nearest to the trolley wire, a guard wire should be erected on span wires or on the brackets. This indicates the minimum requirements. In very exposed situations or for heavy routes of wires, more than one guard wire may be needed.

10. When guard wires are attached to other supports than the trolley poles they should be connected with the rails at one point at least.

11. When it is possible that a telegraph wire may fall on an arm or a stay, or a span wire, and so slide down on to a trolley wire, guard hooks should be provided.

General

12. Minimum guarding requirements for Classes (*a*) and (*b*) are provided for in this memorandum, but in exceptional cases, such as in very exposed positions, or for unusually heavy telegraph wires, special precautions should be taken.

APPENDIX II

ABSTRACTS FROM THE STANDARDS OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Railway Motors

Rating

101. The **one-hour rating** of a railway motor shall be the output at the motor shaft measured in horse power (or kilowatts) which the motor can carry for one hour on a stand test, starting cold, at its rated voltage (and frequency in the case of an alternating-current motor) with the ventilation system as in service, without exceeding the temperature limits given in the accompanying table.

102. The **continuous rating** of a ventilated motor shall be the output at the motor shaft measured in horse power (or kilowatts) which the motor can carry for an unlimited period on a stand test, with the ventilating system as in service, without exceeding the temperature limits given in the table.

104. In the absence of any specification as to the kind of rating the one-hour rating shall be understood.

105. The ratings of a **field-control motor** shall relate to its performance with the field connection which gives the maximum rating.

Item	Type of Enclosure	Method of Temperature Determination	Limiting Temperature Rise ° C. One-hour rating A*	One-hour rating B*	Continuous rating A*	Continuous rating B*
Armature and field windings	Ventilated	Resistance Thermometer	100 80	120 95	85 65	105 80
	Totally enclosed	Resistance Thermometer	110 90	130 105	95 75	115 90
Cores and mechanical parts in contact with, or adjacent to, insulation	Ventilated Totally enclosed	Thermometer Thermometer	90 95	95 105	65 75	80 90
Commutator	Ventilated Totally enclosed	Thermometer Thermometer	95 105	110 120	80 90	95 105

* A denotes "Class A" insulation, i.e. cotton, silk, paper, and similar organic substances when impregnated; also enamel as applied to conductors.
B denotes "Class B" insulation, i.e. inorganic materials (mica, asbestos) in built up form, combined with binding substances. If Class A material is used in small quantities for structural purposes only the combined material may be considered as Class B, provided that the electrical and mechanical properties of the insulated winding are not impaired by the application of the temperature permitted for Class B.

Temperature Limitations

(Note.—The **allowable temperature** in any part of a motor in service is governed by the kind of material with which that part is insulated. In view of space limitations, and the cost of carrying dead weight on cars, it is considered good practice to operate railway motors for short periods at higher temperatures than would be advisable in stationary motors.)

1. The **limiting observable temperatures recommended for service** are—

	Normal Values	*Peak Values*
Class A insulation	90–105° C. (thermo.)	110–125° C. (resistance)
Class B insulation	105–120° C. (thermo.)	130–145° C. (resistance)

The "normal" values are those which will be obtained in normal service with cooling air at a temperature of 25° C. The "peak" values are those which will usually be found with maximum motor loads and highest cooling air temperatures. In each case the lower limit refers to the temperature as determined by thermometer, and the upper limit refers to the temperature as determined by resistance measurements.

150. The **temperature rise of each of the various parts** above the temperature of the cooling air, **when tested in accordance with the rating,** shall not exceed the values given in the table. The resistance method of temperature measurement is considered as the basic method.

153, 156. The resistance method of temperature determination involves the comparison of the resistance at the temperature to be determined with the resistance at a known temperature. If t = reference temperature ° C., r = resistance at reference temperature, R = observed resistance, then temperature (T) corresponding to observed resistance is given by

$$T = (R/r)(234{\cdot}5 + t) - 234{\cdot}5.$$

157. The test may be made at any cooling air temperature, preferably not below 10° C. It shall be assumed that the temperature rise is the same for all cooling air temperatures between the limits 10° and 40° C.

162. (1) The cooling air temperature of all motors, except those equipped with inlet pipes or ducts, shall be measured by several thermometers placed at different points around and half-way up the machine at a distance of 1 to 2 metres.

(2) When the cooling air is supplied through ducts the temperature of the cooling air shall be measured in the inlet duct system at a distance of not less than one metre from the machine.

Characteristic Curves

350. The **characteristic curves** of railway motors shall be plotted with the current as abscissae, and the tractive effort, speed, and efficiency as ordinates. In the case of alternating-current motors, the power-factor shall also be plotted as ordinates.

351. **Characteristic curves of direct-current motors** shall be based on full rated voltage.

352. **In the case of field-control motors,** characteristic curves shall be given for all operating field connections.

Efficiency and Losses

201. The following **method of determining efficiency** is recognized as standard for direct-current railway motors—

Conventional efficiency.—The efficiency is obtained from the component losses, most of which are accurately determinable and the remainder of which are assigned conventional values.

202. **Normal conditions for conventional efficiency tests** and calculations—

(*a*) The efficiency shall be determined for the rated voltage.

(*b*) When the efficiency is stated without specific reference to load conditions, the 1-hour load shall be understood.

(*c*) The efficiency of all apparatus at all loads shall be corrected to a reference temperature of 75° C., but tests may be made at any convenient cooling air temperature, preferably not less than 10° C.

203. Conventional efficiencies shall be based upon the following losses*—

(*a*) I^2R losses in armature and field windings; (*b*) brush friction, armature bearing friction, and windage losses; (*c*) no load core loss; (*d*) brush contact loss; (*e*) stray load losses.

* When the efficiency of the motor, including the losses in the gearing, is required, the conventional values given in §400 should be included.

204. **Losses** shall be measured, calculated, or arbitrarily taken as specified in §§ 205–209.

205. The **I²R losses** shall be based upon the current and the measured resistance, corrected to 75° C.

206–7. The **no-load core loss, brush friction, armature-bearing friction and windage** shall be determined as a total under the following conditions—

In making the test, the motor shall be run without gears. The kind of brushes and the brush pressure shall be the same as in commercial service. With the field separately excited, such a voltage shall be applied to the armature terminals as will give the same speed for any given field current as is obtained with that field current when operating at normal voltage under load. The sum of the losses above-mentioned is equal to the product of the counter E.M.F. and the armature current.

The no-load core loss is determined from the total losses thus obtained by deducting the power required to drive the motor light at the corresponding speeds. (For this test the machine is run as a series motor at low voltage. The product of the counter E.M.F. and the current at any speed shall be the sum of the brush friction, armature bearing friction, and windage losses.)

208. **Brush contact loss.** A total drop of three volts shall be assumed as the standard drop in determining brush contact loss for carbon and graphite brushes where no shunts (pigtails) are attached. Two volts drop shall be allowed where shunts are attached.

209. The stray load losses are given conventional values, as follow—

Input (% of 1-hour rating) . .	200	150	100	75	50	25 (and under)
Stray load loss (% of no load core loss)	65	45	30	25	23	22

400. The **losses in gearing and axle bearings** for single-reduction, single-geared motors varies with type, mechanical finish, age, and lubrication. The following values, based on accumulated tests, shall be used in the comparison of single-reduction single-geared motors—

Input (% of 1-hour rating) .	200	150	100	75	60	50	40	30	25
Losses (% of input) . .	3·5	3·0	2·5	2·5	2·7	3·2	4·4	6·7	8·5

Dielectric Test

250. The standard test voltage shall be twice the rated voltage of the motor, plus 2000 volts, with alternating current of commercial frequency.

252. The test voltage shall be applied continuously for a period of 60 sec.

255. High-voltage tests shall be made at the temperature assumed under normal operation, or at the temperature attained under the conditions of commercial testing.

NOTES ON THE BRITISH ENGINEERING STANDARDS ASSOCIATIONS' SPECIFICATION FOR THE ELECTRICAL PERFORMANCE OF TRACTION MOTORS

Rating

The definitions of the **one-hour and continuous ratings** are similar to those given on p. 695, with the additional qualifications: (1) the continuous rating of a ventilated motor shall refer to the output at rated voltage; (2) the continuous rating of a totally enclosed motor shall refer to the output at one-half of the rated voltage; (3) in the case of field control motors, the ratings shall be associated with a stated condition of excitation and corresponding speed.

Temperature Limitations

The **permissible temperature rise** of a motor when tested under conditions in accordance with the rating shall not exceed the limits given in the

accompanying table. The resistance method of temperature measurement shall always be employed where possible.

Item	Method of Temperature Determination	Limiting Temperature Rise ° C.			
		One-hour rating		Continuous rating	
		A*	B*	A*	B*
Armature and field windings	Resistance Thermometer	100 75	120 95	85 65	105 85
Commutator	Thermometer	90		85	
Core	Thermometer	120		105	

NOTE.—The above temperature rises are not intended to have reference to service.

Characteristic Curves and Efficiency

The **rated speed** and the **characteristic speed curve** of the motor should be corrected to a motor temperature of 75° C. as measured by resistance. The rated speeds (at the continuous and one-hour loads) shall not differ from the declared speeds by more than $\pm$ 3 per cent. Any statement of **efficiency** shall be based upon direct measurement and shall be corrected to correspond to a motor temperature of 75° C. Unless otherwise stated, the efficiency shall be understood as referring to the motor only, and shall exclude losses due to gearing.

Dielectric Test

The test (r.m.s.) voltage shall be twice the line voltage *plus* 1,000 volts, with a minimum of 2,500 volts, applied for one minute with the motor hot (at the conclusion of the one-hour test), provided that the insulation resistance in megohms is not less than that given by the formula—

Line volts/(1000 + rated output in b.h.p.)

Tests on New Machines

These comprise: One-hour and continuous rating tests, a speed test, an overspeed test (when necessary), and commutation tests. The **overspeed test** is applied when the maximum vehicle speed is declared, the motor being run for one minute at a speed 10 per cent in excess of that corresponding to the declared maximum vehicle speed.

Commutation tests for motors rated at the line voltage include runs of 30 sec. duration in each direction of rotation, (*a*) at rated voltage with a current 100 per cent in excess of the rated (1 hr.) current, and maximum excitation, (*b*) at 25 per cent above rated voltage with rated (1-hr.) current and minimum excitation.

Commutation tests for motors connected in series include 30-sec. runs (as above) at a terminal voltage 50 per cent in excess of the rated voltage with rated (1-hr.) current and maximum excitation.

Commutation tests for regenerative motors include 30-sec. runs (as above) at a terminal voltage 25 per cent in excess of the rated voltage with a current 50 per cent in excess of the rated (1-hr.) current and an excitation which gives the maximum value for the ratio (armature current/field current) within the limits for regenerative operation.

* See note *, page 695.

EXAMPLES

THIS collection of examples includes a large number of numerical questions set at the following examinations—

University of London, B.Sc. Eng.* Reference *L.U.*

City and Guilds of London Institute, Electrical Engineering (Final Grade). Reference *C.G.*

Institution of Electrical Engineers, A.M.I.E.E. Examination.† Reference *I.E.E.*

Battersea Polytechnic, Final Diploma Examination in Electrical Engineering. Reference *B.P.*

The examples have been grouped according to subject-matter.

I. TRAIN MOVEMENT (CHAPTERS II AND III)

1. An electric train runs with an average speed of 22 ml.p.h. The average distance between stations is 1 ml., and the train stops 20 sec. at each station. What is the effect on the schedule speed of doubling the average speed and making the stops 30 sec.? What is the resulting average schedule speed? (*I.E.E.*)

[*Ans.* Schedule speed increased 63·6 per cent. Resulting average schedule speed = 32·1 ml.p.h.]

2. Draw a typical speed-time curve for an electric train for suburban service. State usual values for acceleration and retardation.

On a certain line, with an average of $1\frac{1}{4}$ ml. between stops, the schedule speed is 24 ml.p.h. If the maximum speed attained is 36 ml.p.h., the stops 20 sec., and the retardation 2 ml.p.h.p.s., find the acceleration required. (*C.G.*)

[*Ans.* a = 0·538 ml.p.h.p.s.]

3. Sketch a typical speed-time curve for an electric train operating on suburban service, and give reasons for the shapes of the various portions of the curves. What deductions can be made from the speed-time curve?

A service of trains is to be run at a schedule speed of 17 ml.p.h. over a level route in which the distance between stations is 0·5 ml. The station stops are of 20 sec. duration. Using the simplified (trapezoidal) speed-time curve, calculate the acceleration required to run the service, assuming that the braking retardation is 2 ml.p.h.p.s. and that the maximum speed is 30 per cent greater than the average speed. (*B.P.*)

[*Ans.* a = 1·05 ml.p.h.p.s.]

4. An electric train has a mean running speed from start to stop of 20 ml.p.h.; it accelerates at 1 ml.p.h.p.s. and brakes at 1·75 ml.p.h.p.s. The mean distance between stations is 3000 ft.

Draw an approximate speed-time curve for the run and estimate the energy consumption per ton mile. (*I.E.E.*)

[*Ans.* Speed-time curve—

Time (sec.)	0	24·7	88·2	102·3
Speed (ml.p.h.)	0	24·7	24·7	0

Specific energy output = 48·6 Wh. per ton ml., assuming W_e/W = 1·1, r = 10 lb. per ton.]

* The Engineering Examination Papers of the University of London are published regularly by the University of London Press.

† The Examination Papers are published regularly by the Institution of Electrical Engineers.

5. Distinguish between schedule speed and average speed. On an electrified suburban line the distance between two stations is 1·5 ml. Calculate the maximum speed to be attained to give a schedule speed of 25 ml.p.h. if there is a station stop of 25 sec. The acceleration is 1·5 ml.p.h.p.s. and the braking is 2 ml.p.h.p.s. (*C.G.*)

[*Ans.* 31·3 ml.p.h.p.s.]

6. The draw-bar pull of an electric locomotive hauling a goods train of 320 tons on the level is 1 ton at 20 ml.p.h. What does the pull become on a gradient of 1 in 80 in order to keep the speed the same up the grade as on the level? (*I.E.E.*)

[*Ans.* 5 tons.]

7. An electric train weighing 220 tons (dead weight) makes a run on the level between two stations 1·2 ml. apart. The initial acceleration is 1·2 ml.p.h.p.s. and the braking retardation is 2 ml.p.h.p.s. The run is made to a trapezoidal speed-time curve and the free-running speed is 20 per cent above the average speed. Draw to scale the speed-time curve and calculate the power output (*a*) at the end of the accelerating period, (*b*) during free-running. Calculate also (*c*) the specific energy output for the run. Assume the effective weight of train as 10 per cent greater than the dead weight, and the train resistance at 10 lb. per ton at all speeds. (*B.P.*)

[*Ans.* Speed-time curve—

Time (sec.) . . .	0	30	126	144
Speed (ml.p.h.) . .	0	36	36	0

(*a*) 2290 kW., (*b*) 158 kW., (*c*) 52 Wh. per ton ml.]

8. What is meant by the effective weight of a car or train? A traction motor weighing 6000 lb., with an armature which is 20 in. in diameter weighing 2200 lb., drives wheels 44 in. in diameter through 57 : 20 gearing. Calculate approximately the effective weight of the motor. (*I.E.E.*)

[*Ans.* 7800 lb.]

9. Calculate the tractive-effort necessary for the *angular* acceleration of the armature of a motor geared to 36 in. driving wheels (the gear ratio being 4·43 :1) when the linear acceleration of the latter is 1·2 ml.p.h.p.s. Weight of armature, 1650 lb.; diameter of armature, 17·5 in. (*B.P.*)

[*Ans.* 207 lb.]

10. An electric train consists of n motor coaches, each weighing W_1 tons, and m motor coaches, each weighing W_2 tons. Each motor coach is equipped with p geared motors, the armatures of which weigh W_3 tons each, the gear ratio being γ. All wheels are of the same diameter and weight. Deduce expressions for (*a*) the accelerating weight of this train, (*b*) the accelerating tractive effort on level track, (*c*) the accelerating tractive effort on gradients. (*B.P.*)

11. Calculate the effective weight of the six-coach train of which data follow—

Composition of train.—2 motor coaches, 4 trailer coaches.

Motor coaches.—Weight, 27·5 tons. Equipment: one 4-wheel motor truck with 36 in. wheels and two 200-h.p. motors, gear ratio 3·2 :1; one 4-wheel trailer truck with 30 in. wheels. Diameter of armatures, 18·5 in. Weight of armatures, 1800 lb. each.

Trailer coaches.—Weight, 16·2 tons. Equipment: two 4-wheel trucks with 30-in. wheels.

Weight of wheels: 36 in., 900 lb. each; 30 in., 650 lb. each. (*B.P.*)

[*Ans.* 133 tons.]

12. The following data refer to the speed-time curve of an electric train for the run on level track between two stations on a suburban railway—

Time (sec.) .	0	18	20	23	28	33	38	62·6	76
Speed (ml.p.h.) .	0	18·7	20·6	23	26	28·2	30	27·1	0

Determine the energy output, in kWh., from the driving axles for the run. Determine also the energy output per ton mile.

The dead weight of the train is 150 tons, and the effective weight is 166 tons. Train resistance may be assumed at a constant value of 10 lb. per ton. (*B.P.*)

[*Ans.* 4·65 kWh.; 71·3 Wh. per ton ml.]

II.—MOTORS (CHAPTERS IV–VII)

1. What speed-torque characteristics are desirable for traction motors operating suburban services, and what electrical characteristics are desirable when the axles of a car or coach are to be driven by separate motors operating in parallel? (*B.P.*)

2. What are the outstanding constructional features in a typical direct-current railway motor? Explain why these features are necessary in a railway motor and are not usually found in an industrial motor. Give sketches showing longitudinal and cross-sectional views of a railway motor. (*B.P.*)

3. The armature of a 40 b.h.p. traction motor has 41 slots and about 1000 conductors. Find a suitable winding pitch and show the arrangement of the conductors in the slots. How many segments should be employed if the commutator has a diameter of 11 in.? (*L.U.*)

[*Ans.* Number of commutator segments = 123 (i.e. 3 segments per slot). Number of conductors = 984 (i.e. 24 per slot, arranged 3 × 8). Turns per coil = 4. Winding pitch = 61 coil-sides (each coil-side consists of four conductors). Slot pitch = 10 slots (i.e. coil-sides Nos. 1 and 62, belonging to coil No. 1, occupy slots Nos. 1 and 11 respectively).]

4. The 500-volt motors on a tramcar have resistances of 0·3 ohm and 0·2 ohm for field and armature respectively. When running in full parallel, at an efficiency of 88 per cent and at 660 r.p.m., each develops a torque of 180 lb.-ft. Determine the percentage weakening of the field required to increase the speed to 720 r.p.m., the torque remaining unchanged. (*L.U.*)

[*Ans.* 8·7 per cent.]

5. A two-axle tramcar is equipped with two standard d.c. series motors. If the wheels on one axle wear much quicker than those on the other axle, how would the motors share the load (*a*) in series, (*b*) in parallel?

If, in addition, the motor driving the smaller wheels had a speed characteristic slightly higher than that of the other motor, how would this affect the sharing of the load? State full reasons for the answers given. (*I.E.E.*)

6. The following motor characteristic is based on a wheel diameter of 36 in.—

Current (amp.) . . .	80	160	240	320	400
Tractive effort (lb.) . .	400	1350	2470	3700	4950
Speed (ml.p.h.) . .	53	34·5	28·8	25·5	23·2

A motor bogie is fitted with two of these motors, one pair of wheels being 36 in. in diameter and the other pair 35 in. The motors are operated on the series-parallel system. Suppose the tractive effort at the 36-in. wheels is 3000 lb., what will be the current and tractive effort of the other motor (*a*) in full series, and (*b*) in full parallel? (*I.M.E.*)

[*Ans.* (*a*) 277 A., 2925 lb.; (*b*) 259 A., 2675 lb.]

7. The motor-coach of an electric train is equipped with two geared

motors having characteristics at 775 V. and for 42 in. driving wheels, as follow—

Amperes input per motor .	250	200	150	100
Speed of car (ml.p.h.) . .	20·2	22	24·7	32·2
Tractive effort (lb.) . .	4200	3100	2065	1005
Efficiency (per cent) . .	87·5	88	87·7	83·5

The diameters of the driving wheels connected to one motor (A) are 42 in. and those connected to the other motor (B) 40 in. When the motors are operating in parallel at a train speed of 24 ml.p.h., determine (a) the power input to each motor, (b) the tractive effort, and (c) output at each pair of driving wheels.

Determine also the corresponding quantities for series operation when the current input is 150 A. The resistance of each motor is 0·15 ohm. (*B.P.*)

[*Ans.* Parallel operation: (a) 124 kW. (A), 112·4 kW. (B); (b) 2270 lb. (A), 2050 lb. (B); (c) 109 kW. (A), 98·4 kW (B). Series operation: (a) 56·8 kW. (A), 59·5 kW. (B); (b) 2065 lb. (A), 2170 lb. (B); (c) 48·3 kW. (A), 50·7 kW. (B). NOTE—Train speed for series operation (150 A.) = 11·69 ml.p.h.]

8. Discuss the general advantages and disadvantages of tapped or shunted field operation of d.c. traction motors. A motor has characteristics as follow—

Amperes . . .	300	250	200	150	100
Tractive effort (lb.) . .	3250	2500	1780	1100	500

Deduce the corresponding characteristics for the motor with one-third of its exciting field cut out. (*I.E.E.*)

[*Ans.*

Amperes . . .	300	250	200	150	100
Tractive effort (lb.) .	2670	1975	1320	750	330

HINT—Calculate the tractive effort per ampere ($= k\Phi$) and plot against exciting current. Thence determine $k\Phi$ for the exciting currents with the tapped field winding. The tractive efforts are then obtained by multiplying the appropriate values of $k\Phi$ by the corresponding armature currents.]

9. What is the effect on its service performance of shunting the field of a series traction motor? What are the relative advantages of shunting and tapping the field?

The characteristics of a motor are given in Example V, 9. Draw the new characteristics with the field shunted 30 per cent. (*I.E.E.*)

[*Ans.*

Amperes . . .	80	160	240	320	400
Tractive effort (lb.) . .	272	1040	2080	3200	4370
Speed (ml.p.h.) . .	82·3	44·8	34·2	29·5	26·3]

10. What type of alternating-current motor is employed for single-phase electric traction? Discuss briefly the principal features in the construction of this motor, and show how good commutation and a high power factor are obtained. Draw a vector diagram for the motor. (*B.P.*)

11. Two locomotives, equipped with $16\frac{2}{3}$-cycle, 3-phase induction motors, are hauling a train. The rated output of each locomotive is 1000 h.p., at which the slip is 4 per cent. One locomotive has new wheels of 1·5 M. diameter, and the other has wheels with 1·5 cm. radial wear. Estimate the distribution of load between the locomotives when the track conditions demand total outputs of (a) 2000 h.p., (b) 1000 h.p., (c) 100 h.p. How could a more equal distribution be obtained? (*I.E.E.*)

[*Ans.* (a) 1130, 870; (b) 620, 380; (c) 180, – 80 h.p.]

12. The cold resistance of the main fields of a motor is 0·0431 ohm, measured at an air temperature of 12° C., and the hot resistance is 0·0526 ohm measured at an air temperature of 17° C. What is the temperature rise? The resistance coefficient is 1/234·5 at 0° C. (*I.E.E.*)

[*Ans.* 82° C. HINT—$R_\theta = R_0\,(1 + \theta/234{\cdot}5)$]

13. What is meant by the one-hour rating and the continuous rating of a traction motor? Of what use are these ratings in deciding if a motor is adequate for a given service? The cold resistance of the armature winding of a traction motor is 0·04885 ohm at 7° C. The resistance at the end of the one-hour test is 0·0708 ohm, the air temperature being 15° C. What is the rise in temperature of the armature winding? The resistance coefficient is 1/234·5 at 0° C. (*I.E.E.*)

[*Ans.* 100° C.]

14. Give the fundamental principles of two types of tooth form used for traction motor gearing.

A traction motor is designed with a pinion having 14 teeth and a gear wheel having 70 teeth, the diametrical pitch being 2½. What are the diameters of the pitch circles of pinion and gear wheel? Also what would be the gear ratio if the number of teeth in the pinion were changed to 17, the gear centres and the diametrical pitch remaining the same? (*I.E.E.*)

[*Ans.* 5·6″, 28″. 3·94:1.]

15. Describe with sketches the application of roller bearings to the armature of a traction motor. What are the advantages and disadvantages of these bearings compared with ordinary sleeve bearings? (*I.E.E.*)

III—Control (Chapters VIII–XII)

1. Explain the series-parallel system of control as applied to electric traction. Neglecting the resistances of the motors, show that, with constant motor current and constant line voltage, the rheostat losses during starting two motors on the series-parallel system are one-half of those when the motors are started on the rheostatic system (i.e. both motors in parallel throughout the starting period).

Explain the various methods of transition from series to parallel, and mention the suitability of these methods for (*a*) tramway service, (*b*) suburban railway service with motor-coach trains. (*B.P.*)

2. What are the advantages of the series-parallel system of control as applied to electric traction by means of direct currents? Give diagrams showing the connections made at each step during starting and braking. Show by a diagram what is the saving in energy secured by this method during starting. What further saving can be secured by using four motors instead of two? (*L.U.*)

3. Show by diagrams how the motors on a tramcar are connected during (*a*) starting, (*b*) running, (*c*) electric braking. Describe how the retardation during electric braking is controlled, and explain what provision is usually made in the control system to prevent a car running backwards downhill. (*B.P.*)

4. Some tramway companies are changing from the ordinary drum-type controller to a hand-operated cam controller. Give reasons for this. Describe briefly a hand-operated cam controller for tramway use. (*I.E.E.*)

5. A car driven by two direct-current series motors is taking 58 A. from a 500-V. line with the motors in full series. The motors are switched into parallel through a resistance; calculate the value of this resistance in order that the transition may be effected without shock. The total resistance of each motor is 0·5 ohm.

In the control of heavy direct-current traction motors, what modification of the mode of transition from series to parallel is necessary as compared with the methods used for tramway motors? Explain why this modification is required, and how it is carried out in practice. Give a diagram of connections. (*L.U.*)

[*Ans.* 4·06 ohms.]

6. Describe a method of determining the number of notches required in a multiple unit equipment.

On a motor-coach there are two motors: the resistance of each motor is 0·15 ohm, the maximum permissible starting current per motor is 400 A., and the average current is 350 A. Assuming the voltage is constant at 600 V. during starting, and that for the range considered the flux is proportional to the fourth root of the current, what are the values of the resistances required for the first and second notches in series? (*I.E.E.*)

[*Ans.* Resistance of rheostats for first notch = 1·2 ohm
,, ,, second ,, = 0·8 ohm]

7. What should be the special characteristics of rheostats for starting d.c. electric goods locomotives?

It is desired to arrange for starting a certain locomotive and train so that the tractive effort is within given limits. At the upper limit the speed of the locomotive with motors in full series is 6·8 ml.p.h., and the resistance drop in the motor is 12 per cent of its terminal voltage. At the lower limit the speed is 7·1 ml.p.h., and the resistance drop 10 per cent of the terminal voltage. How many series notches are necessary in the control? (*I.E.E.*)

[*Ans.* 10. Hint—Use equation (vii), p. 259. Note $\lambda = 0{\cdot}85$, $\gamma = 0{\cdot}833$, $e/V = 0{\cdot}12$, $\zeta = 1{\cdot}0$.]

8. Determine the magnitudes of the resistances for the series notches of a tramcar controller to control two 40-h.p., 500-V. motors. The (hot) resistance of each motor is 0·65 ohm; the current limits during acceleration are 88 and 60 A.; and the speeds of the car corresponding to these currents are 8·7 and 10·2 ml.p.h., respectively, with normal voltage on each motor. (*B.P.*)

[*Ans.* $R_1 - R_2 = 1{\cdot}93$ ohms; $R_2 - R_3 = 1{\cdot}43$ ohms; $R_3 - R_4 = 1{\cdot}02$ ohms.]

9. Calculate the resistances of the series sections of the starting rheostat for the series-parallel control of two railway motors having characteristics as given in Example V, 13, the number of steps in the series portion of the controller being five. The initial starting current is 300 A., and the upper and lower limits of current during starting are 350 A. and 253 A. respectively. The resistance of each motor is 0·1 ohm. (*B.P.*)

[*Ans.* $R_1 - R_2 = 0{\cdot}538$; $R_2 - R_3 = 0{\cdot}435$; $R_3 - R_4 = 0{\cdot}353$, $R_4 - R_5 = 0{\cdot}286$ ohm.]

10. Calculate the resistances of the sections of the starting rheostats for the series-parallel control of two 225 h.p., 600-V., direct-current traction motors. The motor controller is arranged for automatic notching; there are five series and four parallel steps, and bridge transition is employed. The initial starting current is 300 A. The upper limit of current is 348·7 A. for the series steps and 326 A. for the parallel steps. The lower limit of current on all steps is 251·3 A. Each motor has a resistance of 0·12 ohm, and the speeds (at 600 V.) corresponding to the currents 348·7, 326, and 251·3 A. are 17·9, 18·4, and 20·5 ml.p.h.

[*Ans.* Calculated resistances of sections (per motor)—*Series*: $R_1 - R_2 = 0{\cdot}2955$, $R_2 - R_3 = 0{\cdot}238$, $R_3 - R_4 = 0{\cdot}912$, $R_4 - R_5 = 0{\cdot}1545$ ohm. *Parallel*: $R_{1p} - R_{2p} = 0{\cdot}32$, $R_{2p} - R_{3p} = 0{\cdot}269$, $R_{3p} - R_{4p} = 0{\cdot}226$ ohm. Note—A complete solution is given in *Journ. I.E.E.*, Vol. 60, p. 881.]

11. What are the conditions which determine that d.c. series traction motors will act as generators and thus provide a rheostatic brake?

Discuss briefly the effect of (*a*) the direction of residual magnetism, (*b*) the speed, and (*c*) the value of resistance in circuit. Illustrate with diagrams. (*I.E.E.*)

12. Give diagrams and explain how the motors and magnetic brakes on a tramcar are connected for electric braking. How is the braking effect controlled, and how is skidding of the wheels prevented when braking the

car at high speeds? Explain carefully what changes in the connections of the motors are made when the controller drum is moved from the first power position to the first brake position. (*B.P.*)

13. A d.c. series motor is to be used for rheostatic braking on a tramcar. With the field separately excited on test, the open-circuit voltage across the armature at a speed corresponding to 15 ml.p.h. was —

Field amperes . . .	10	20	40	60	80
Armature volts . .	145	280	500	630	700

When the machine is being used for braking on the tramcar, what external resistance would have to be put in the motor circuit to obtain a current of 70 A. at a speed of 10 ml.p.h.? The resistance of the motor armature and field windings can be neglected.

What would be expected to happen if a resistance of 25 ohms were put in the motor circuit when the car was running at 15 ml.p.h. (*I.E.E.*)

[*Ans.* 6·32 ohms. Machines would not excite.]

14. A motor having a resistance of 0·16 ohm and characteristics at 675 V. as given in Example II, 6, is used for rheostatic braking. Omitting resistance losses, the efficiency of the machine may be taken as 92 per cent. It is required to obtain a braking effort at the wheel treads of 3000 lb. at a speed of 30 ml.p.h. What current and voltage will be generated, and what will be the necessary external resistance. (*I.E.E.*)

[*Ans.* Current = 243 A. Terminal voltage = 625 A. External resistance = 2·57 ohm.]

15. Compare the methods in general use for controlling the speed of electric trains equipped with (*a*) direct-current motors, (*b*) single-phase motors. Draw diagrams showing the principal main-circuit connections for two typical cases. (*B.P.*)

16. Describe the methods of regenerative control met with in direct-current and in alternating-current traction, and criticize their advantages and disadvantages. Illustrate your answer by suitable diagrams of connections. (*L.U.*)

17. Explain, with sketches, the method of operating a railway train by three-phase induction motors working with "cascade" connections, and describe the gear which is used for starting. What are the chief objections to this system? (*C.G.*)

18. A car, driven by a three-phase induction motor, ascends a gradient of 1 in 10 at a speed of 8 ml.p.h. The frictional resistances are equivalent to a gradient of 1 in 50. The motor on no load and normal voltage has a power factor of 0·15 and at standstill a power factor of 0·25. The standstill current is 30 times the no-load current, and the current taken under the given conditions of running is four times the no-load current. At what speed will the car run with the same current on a "down" gradient, and what is the value of this gradient? (*L.U.*)

[*Ans.* 8·28 ml.p.h. Down gradient: 14·5 per cent or 1 in 6·9. HINT.—Draw circle diagram. Assume I^2R losses at standstill to be equally divided between stator and rotor. Determine slips as motor and generator, speed as generator, and ratio: (output as motor/input as generator). Equate given conditions.]

IV.—ROLLING STOCK AND LOCOMOTIVES (CHAPTERS XIII–XVII)

1. Sketch and describe one good form of magnetic track brake for use on a tramway, and show how it is energized. Calculate the vertical pull and estimate the horizontal drag exerted if the area of each pole is 5 sq. in. and in which the iron is magnetized to an induction density of 18,000 C.G.S. units. (*L.U.*)

[*Ans.* Vertical pull = 0·83 ton. Horizontal drag (assuming coefficient of friction = 0·25) = 0·208 ton.]

2. A four-wheel tramcar has 32 in. wheels on a 6 ft. 6 in. wheel base. The weight of the loaded car is 14 tons, the mass-centre being 3 ft. above the axle centres. Estimate the maximum acceleration which can be obtained without slip of the front wheels. Coefficient of adhesion, 0·15. Neglect tractive resistance and gradient. (*I.E.E.*)

[*Ans.* $a = 2{\cdot}5$ ml.p.h.p.s.]

3. What is the effect on the weight distribution on a motor bogie of the thrust on the bogie centre caused by the motors or by braking? A bogie has a wheel base of 7 ft., and the height of the bogie centre above the rail is 3 ft. 6 in. The total weight on the wheels is 25 tons, and the horizontal thrust at the bogie centre due to the motors is 5 tons. Calculate the approximate loads on the two axles, stating the assumptions made. (*I.E.E.*)

[*Ans.* 7·5 tons, 17·5 tons.]

4. What is meant by the adhesive weight of a locomotive? A locomotive weighs 120 tons, of which 80 tons is adhesive weight. What maximum trailing load will this locomotive haul at a steady speed up a 1 per cent gradient, assuming a track resistance of 10 lb. per ton. (*I.E.E.*)

[*Ans.* 986 tons assuming coefficient of adhesion = 20 per cent.]

5. The coefficient of adhesion for an electric locomotive is 0·25. A locomotive is required to start a trailing load of 600 tons up a gradient of 1 per cent with an acceleration of 0·2 ml.p.h.p.s., the track resistance is 10 lb. per ton and the ratio of effective weight to dead weight of the whole train is 1·1:1. What is the minimum adhesive weight required on the locomotive? (*I.E.E.*)

[*Ans.* 65 tons. Note—Weight of locomotive assumed to be 65 tons.]

6. An electric locomotive employing geared axle-mounted d.c. motors is required to work goods trains of maximum trailing weight 500 tons on a ruling gradient of 1 in 35, and the weight per axle is limited to 20 tons. Assuming that it is deemed necessary to keep within an adhesive limit of 25 per cent of the weight on drivers, what number of driving axles should be used and what minimum weight should they carry? (*I.E.E.*)

[*Ans.* 4 driving axles; 19·3 tons.]

7. What methods are employed to obtain a number of efficient running speeds in (1) a direct-current locomotive; (2) a single-phase locomotive; (3) a three-phase locomotive?

Give explanatory diagrams of connections and sketch typical speed-torque curves for each case. (*B.P.*)

8. What methods are adopted for transmitting the power from the motors to the driving axles in the case of large single-phase locomotives equipped with two motors only? Sketch one good arrangement for such transmission. (*L.U.*)

9. Discuss the relative merits of high-pressure single-phase and moderate-pressure continuous-current locomotives for main lines, paying particular attention to the following points: (*a*) weight of locomotive per h.p., (*b*) regulation of speed and tractive effort, (*c*) efficiency, (*d*) simplicity of design and operation. (*C.G.*)

10. A train is composed of two motor coaches and one trailer coach. On each motor coach is a motor-generator set giving a low tension supply for lighting. It is necessary to be able (*a*) to light all the train from either motor-generator set, and (*b*) to light each motor coach from its own set and the trailer from either set at the same time. Under these circumstances the switching arrangements must be such that the motor-generator sets cannot be connected in parallel. Draw a diagram of connections showing how this can be done. (*I.E.E.*)

11. State the advantages of a low-step tramcar and explain what effect this type of car has had on traction motor design.

The maximum safe speed of the armature of a motor is 8000 ft. per min., measured on the periphery, the number of teeth in the gear wheel is 70, and in the pinion 14; the armature diameter is 14 in., and the diameter of the car wheel is 33 in. To what maximum speed is the car limited by the armature? (*I.E.E.*)

[*Ans.* 42·8 ml.p.h.]

V.—Service Characteristics, Speed-Time Curves and Energy Consumption (Chapters XVIII and XIX)

1. On a suburban railway the stations are approximately half a mile apart and the train weight is 200 tons. Enumerate the several factors which limit the maximum number of trains per hour. Discuss the cases where the railway operates (1) between two terminal stations, (2) on a continuous loop without terminal stations.

Explain precisely the manner in which the above factors affect these cases and the extent to which economic and traffic conditions are involved. (*L.U.*)

2. What considerations determine the size of motor and the number of motors for an electric train operating on a suburban railway, full details of the service and the approximate weight of the train being known? What calculations and what factory tests should be made to ascertain if a given motor is suitable for a given service? (*L.U.*)

3. Describe briefly the considerations which fix (*a*) the horse-power, (*b*) the gear ratio of a motor for an electric train. What are the consequences of an unsuitable gear ratio? (*I.E.E.*)

4. A 15-ton car, driven by two series motors in parallel, takes 120 A. from a 500-V. line in ascending a gradient of 1 in 15 at a speed of 10 ml.p.h. The gear ratio is 4·73:1. If this ratio be changed to 5·25:1, find the speed of the car and the current taken when ascending the same gradient. The resistance to traction is 20 lb. per ton, and it can be assumed that, over the required range, the speed of the motor is inversely proportional to the current taken. (*L.U.*)

[*Ans.* 9·46 ml.p.h.; 114·5 A.]

5. Two direct-current motors, each rated at 40 h.p., are driving a car weighing 16 tons at 12 ml.p.h. up a gradient of 1 in 40. The tractive resistance is 15 lb. per ton. The resistance of each armature is 0·3 ohm, and that of the field coils of each motor is 0·15 ohm. The motors being in full parallel, and the line pressure 550 V., find the current per motor. The overall efficiency is 75 per cent.

The controller is moved to a tap-field point cutting out 25 per cent of the field turns. Find the alteration in the steady current and speed on the same gradient. Assume that the flux per pole is proportional to the current in the field windings. (*L.U.*)

[*Ans.* Current increases from 66 A. to 76·2 A.; speed increases to 13·85 ml.p.h.]

6. An electric train weighing 300 tons is equipped with 8 motors. If the acceleration is maintained constant, calculate the necessary torque which each motor armature must exert for the train to reach a speed of 35 ml.p.h. in 25 sec. when starting on an up grade of 1·5 per cent. The diameter of the driving wheels is 36 in., the single gearing has a ratio of 3·36, with an efficiency of 78 per cent, and the resistance to traction averages 15 lb. per ton. An allowance of 10 per cent should be made for rotational inertia. (*C.G.*)

[*Ans.* 4415 lb.-ft.]

7. A tramcar weighing 15 tons is equipped with two motors having the following characteristics—

Amperes per motor	80	70	60	50	40	30	20
Speed of car (ml.p.h.)	9	9·5	10·3	11·5	13·2	16·2	21
Tractive effort (lb.)	1850	1550	1250	940	650	400	200

What is the maximum schedule speed of the car when operating on level track with eight stops per mile, the duration of each stop being 8 sec.? The initial, or rheostatic, acceleration and the braking retardation are to be 1·5 ml.p.h.p.s., and there is no coasting period. The tractive resistance may be assumed to be 25 lb. per ton at all speeds, and the inertia of the rotating parts may be assumed to be equivalent to 10 per cent of the dead weight. (*L.U.*)

[*Ans.* 9·75 ml.p.h.]

8. An electric train weighs 150 tons and has four motors. The gear ratio is 4·7, with an efficiency of 75 per cent, the diameter of the car wheels being 30 in. With the maximum permissible starting current, each motor exerts an armature torque of 2200 lb.-ft. Assuming that the train accelerates uniformly, find the time taken to reach a speed of 30 ml.p.h. when starting on an up-grade of 1 in 100. Allow 10 per cent for rotational inertia and a tractive resistance of 20 lb. per ton.

Ordinary series-parallel control is used. What percentage of the input to the motors is wasted in the controller resistances during starting? (*C.G.*)

[*Ans.* 27·4 sec.]

9. A train weighing 120 tons is fitted with four motors each having a one-hour rating of 252 A. and the following characteristics on the line voltage of 675—

Current (amp.)	80	160	240	320	400
Tractive effort (lb.)	400	1350	2470	3700	4950
Speed (ml.p.h.)	53	34·5	28·8	25·5	23·2

Assume an average current of 35 per cent above the one-hour rating during the rheostatic period, a track resistance of 10 lb. per ton, and braking at 2 ml.p.h.p.s.

(*a*) What is the minimum time in which an average section of 0·75 ml. can be accomplished?

(*b*) Draw in the speed-time curve for an average running speed of 24·5 ml.p.h. (*I.E.E.*)

[*Ans.* (*a*) 99 sec.

(*b*)

Time (sec.)	0	22·9	26·3	33·3	44·7	47	96·2	112
Speed (ml.p.h.)	0	24·9	28	32	36	37	31·8	0

NOTE—Apparent train resistance during coasting assumed at 12 lb. per ton.]

10. A train has a total weight of 308 tons and is equipped with 8 motors, each of 300 h.p. The characteristics of the motor are—

Current (amp.)	100	200	300	400	500
Speed (ml.p.h.)	65	36·5	29·8	26·5	24·7
Tractive effort (lb.)	330	1450	2740	4100	5450

The ratio of effective weight to the dead weight of the train is 1·1 :1. The mean accelerating current is 415 A. per motor. The braking retardation is 1·75 ml.p.h.p.s., and the train resistance can be assumed as 10 lb. per ton throughout the run. Draw the speed-time curve for a run on the level of 1·1 ml. to be made in 152 sec. Calculate the r.m.s. current per motor for the run. (*I.E.E.*)

[*Ans.* Speed-time curve—

Speed (ml.p.h.)	0	26·2	28·5	32	35	36·3	27·5	0
Time (sec.)	0	29·3	32·3	38·9	47·3	52	16·3	152

R.m.s. current per motor = 217 A.]

11. A train driven by d.c. motors and using series-parallel control is accelerated to a speed of 20 ml.p.h. in 25 sec., with a tractive effort of 3000 lb. per motor. Determine the approximate energy, in kWh., lost in the starting rheostats of each pair of motors, at each acceleration. (*I.E.E.*)

[*Ans.* 0·417.]

12. A 200-ton multiple-unit train has eight motors, each taking an average current during notching of 400 A. and developing a gross tractive effort of 3500 lb. Series-parallel control is used, the final voltage across each motor being 550 V. when the speed is 24 ml.p.h. The resistance of each motor is 0·1375 ohm. If the train accelerates on level tangent track against a constant tractive resistance of 10 lb. per ton, find for each motor (*a*) the energy lost in the starting rheostat; (*b*) the motor heating loss; and (*c*) the output (including friction, etc.). Estimate also (*d*) the speed at which transition is made from series to parallel connection, and (*e*) the total accelerating time. Allow 10 per cent for the additional inertia of rotating parts. (*I.E.E.*)

[*Ans.* (*a*) 1037 kW. sec., (*b*) 220 W., (*c*) 168 kW. (max.), (*d*) 10·55 ml.p.h., (*e*) 20·7 sec.]

13. A six-coach electric train, consisting of two motor coaches and four trailers, operates on an underground tube railway at a schedule speed of 15 ml.p.h. with stops of 15 sec. duration. Calculate the speed-time curve and energy consumption of this train for a run between two stations 0·38 ml. apart, assuming the train to be supplied at a constant voltage of 550 V. and the track to be level and straight.

The weight of train with passengers is 138·5 tons and the effective weight is 151·7 tons. Each motor coach is equipped with two 200-h.p., 550-V. motors, which are geared to 36-in. wheels, the gear ratio being 3·37 : 1. The characteristics of the motors at 550 V. are—

Amperes . .	350	300	250	200	150	100
Speed (ml.p.h.) .	17·5	18·7	20·1	22·9	27·5	37·4
Tractive effort (lb.)	4850	3910	3030	2140	1320	590

The average accelerating current per motor is 300 A., the braking retardation is 2 ml.p.h.p.s., the train resistance may be assumed at 8 lb. per ton for all speeds, and the apparent train resistance during coasting may be assumed at 11·3 lb. per ton.

[*Ans.* Speed-time curve—

Time (sec.) . .	0	19·6	23·2	26·2	32·5*	65·1†	76·2
Speed (ml.p.h.) .	0	18·7	21·3	22·9	25·5	22·2	0

Energy consumption—82·6 watt hours per ton mile.]

14. Under actual service conditions the train of the preceding example operates on a graded straight track with stations at the same level. The profile of the track between centres of station platforms, in the direction of running, is as follows—

210 ft. level; 240 ft. 1 in 30 down; 870 ft. level; 480 ft. 1 in 60 up; 210 ft. level.

Calculate the speed-time curve and energy consumption of the train for the actual running conditions, assuming data as above.

[*Ans.* Speed-time curve—

Time (sec.) .	18	20	23·1	28·5*	43·2	53·2	58·9	67·2†	76·2
Speed (ml.p.h.)	18·7	21·1	24	27·1	25·6	22·9	20·4	18	0

Energy consumption—71·8 watt hours per ton mile.]

* Power off. † Brakes applied.

VI.—Trackwork and Overhead Construction (Chapters XXIII–XXV)

1. Sketch and describe a good method for supporting a conductor rail in the case of a direct-current traction system, and indicate its position relative to the running rails. State approximately the electrical conductivity of each of the above types of rail, and the weight in lb. per yard run. (*L.U.*)

2. Explain what is meant by super-elevation. What is the correct value for a train travelling at 30 mi.p.h. on a curve of 500 ft. radius on standard-gauge track? If there were no super-elevation, and the height of the centre of gravity were 5 ft., what would be the ratio of the pressures on the two rails? (*I.E.E.*)

[*Ans.* 1·44″, 1·675 : 1]

3. What considerations determine the permissible sag to be given to a trolley wire for an electric tramway? Calculate the sag to be given to a trolley wire 0·4 in. in diameter and weighing 0·484 lb. per ft. when erected, with a span of 120 ft., if the stress in the wire when erected is 9000 lb. per sq. in. (*B.P.*)

[*Ans.* 9·25″.]

4. The stress in a trolley wire having an area of 0·109 sq. in. is not to exceed 9000 lb. per sq. in. when erected in a span of 120 ft. Calculate the tension that must be allowed, and the resulting sag.

Sketch clearly a method of supporting the wires of a double trolley-bus line round a sharp right-angle bend, without the use of centre poles. (*I.E.E.*)

[*Ans.* 980 lb., 9·25″.]

5. Make sketches of the constructional details for one span of the overhead structure of a single-phase railway in which catenary suspension is used. Show how these details are modified in the case of a curved track. Specify clearly the materials used for the principal parts and the reasons for their selection. (*L.U.*)

6. In a single-catenary construction there is a catenary wire and a trolley wire supported at intervals by droppers. Develop an equation giving the minimum permissible sag in the catenary for a given tension in the catenary wire. (*I.E.E.*)

7. In a catenary system the catenary wire is steel with a maximum permissible tension of 1000 kg. The weight of the catenary wire is 1 kg. per metre run, the weight of the trolley wire is 1·5 kg. per metre run, and the allowance for droppers and fittings is 20 per cent of the trolley wire weight. If the span is 80 metres, what is the minimum sag of the catenary? (*I.E.E.*)

[*Ans.* 2·24 metres.]

8. On an overhead catenary construction with a span of 300 ft. the tension in the catenary wire is 2000 lb. and the sag is 10 ft. With the same weight per foot run, but the span reduced to 280 ft., what would be (*a*) the sag with the same tension, (*b*) the tension with the same sag? (*I.E.E.*)

[*Ans.* (*a*) 8·72 ft. (*b*) 1745 lb.]

VII.—Feeding and Distributing Systems (Chapter XXVI)

1. What are the chief Regulations relating to the supply of power from a central power station to electric tramways? Show how these regulations affect the design of the feeders and distributors for a tramway system with overhead trolley wires and track return. Make a diagram of the negative feeders for such a tramway system supplied direct from a central power station. (*B.P.*)

2. Discuss the causes of electrolytic corrosion of pipes arising from stray currents from a traction system in a large town. What precautions should

be adopted to minimize corrosion (*a*) in matters relating to the pipes, (*b*) in matters relating to the traction system. Show how a negative booster should be connected and operated to reduce stray currents. (*C.G.*)

3. Describe a negative booster for use on a traction system. The resistance of the track rails on a railway is 0·1 ohm per ml., and the normal return current is 500 A. What size of copper feeder would be used in parallel with the rails if the voltage drop is limited to 10 V. per ml., the resistance of copper being 0·75 microhm per in. cube. (*I.E.E.*)

[*Ans.* 1·9 sq. in.]

4. A traction system employs the running rails as return conductors. Describe measures and precautions that may be required to keep the voltage drop within reasonable limits.

It is proposed to take a current of 750 A. from the track, at a point 2000 yd. from the nearest substation, and to use a cable of 0·8 sq. in. cross section. Make a sketch of the booster connections and determine the capacity of the booster. Resistance of copper 0·75 microhms per in. cube. (*I.E.E.*)

[*Ans.* Booster output (assuming feeding point to be at same potential as negative bus-bar) = 38 kW. Connections—see Fig. 454.]

5. In an overhead trolley construction there are two tracks arranged in parallel electrically. Each overhead line has 0·25 sq. in. of copper, and the rails are 90 lb. per yd. (9 sq. in. section) and 10 yd. long. The resistance of each rail joint is equal to that of 1 yd. of rail. The resistance of copper is 0·75 microhm per in. cube, and the resistance of the rail is 11 times that of copper. What is the total resistance per mile of line? (*I.E.E.*)

[*Ans.* 0·111 ohm.]

6. An overhead trolley wire in a tramway system has a resistance of 0·46 ohm per ml., and the maximum permissible voltage drop in a distributing section is 55 V. The cars on the section have a schedule speed of 10 ml.p.h. and there is an interval of 2 min. between the cars. The average current per car is 25 A. Find the length of distributing section corresponding to the maximum voltage drop, assuming the average voltage drop to be 50 per cent of the maximum. (*C.G.*)

[*Ans.* 1 mile.]

7. In a single-catenary system the cross sections of the wires are: copper catenary, 0·2 sq. in.; trolley wire, 0·1 sq. in. The line is single track only, and the starting current of a locomotive is 2000 A. What is the voltage drop in the overhead line when the locomotive starts up between two substations 8 ml. apart, the distance from the locomotive to the nearest substation being 2 ml.? Resistance of copper is 0·75 microhm per in. cube. (*I.E.E.*)

[*Ans.* 475 V.]

8. Explain with connection diagrams one method of connecting overhead feeders and trolley wire for a single-phase railway to reduce interference in adjacent communication circuits. (*C.G.*)

9. On a 1500-V. d.c. railway there are two substations, *A* and *B*, 10 ml. apart. The first 4 ml. of track from *A* is single and the remainder is double. The resistance of the single-track rails is 0·05 ohm per ml. With 200 A. collected by a locomotive running from *A* to *B*, the maximum voltage drop allowed on the system is 100 V. The overhead line has a constant section over each track, and over the double track the overhead lines and track rails are bonded together at frequent intervals. What is the minimum section of the copper in the overhead line between *A* and *B*? Resistance of copper is 0·75 microhm per in. cube. (*I.E.E.*)

[*Ans.* 0·2015 sq. in.]

VIII.—Substations (Chapter XXVII)

1. A fault occurs on a conduit tramway system supplied through sectio feeders. How would you determine at the station whether it is on the mai conductors or on the car? If on the car, show how it is possible to ascertai quickly (*a*) whether the fault is a dead earth or a partial one; (*b*) whether the positive or the negative side; or (*c*) between conductors without earth. (*L.U.*)

2. A tramway area operating at 600 V. is supplied from a substation connected to the generating station by two 11,000-V., 3-phase cables. Draw a diagram of the essential connections of the machinery in the substation Give reasons for your choice of the type of plant, and submit a diagram c the general arrangement of machines and switchgear. (*C.G.*)

3. A rotary converter with six slip rings is fed from the secondaries of three-phase transformer with star-connected primaries. Each primary coi has ten times as many turns as the secondary. A load of 200 A. at 500 V. is taken from the direct-current side. Draw carefully a diagram of the connections, and also a vector diagram showing the magnitude and phase relationship of the voltages of the line, of the transformer coils, and of the slip rings. Calculate the approximate voltages on the mains and the currents in the primary coils. (Assume the efficiency to be 100 per cent and the power factor unity.) (*L.U.*)

[*Ans.* Voltage at slip rings (diametrical), 353; line voltage, 6100; current in primary coils, 9·46 A.]

4. Give a diagram of connections for a substation with transformers and rotary converters for supplying power at 500 V., direct current, the primary supply being 10,000 V., three-phase. Calculate (*a*) the ratio of turns in the transformers; (*b*) the currents in their windings, and in the connections to the slip rings, when working at full load (1000 kw.) with a power-factor of 0·95. (*L.U.*)

[*Ans.* (*a*) Ratio of turns ($\Delta - \Delta$) = 32·6 (*b*) Current in primary windings = 37·8 A., current in secondary windings = 1205 A., current in connections to slip rings = 2090 A. (Assumed efficiencies: rotary converter, 95%; transformers, 98%.)]

5. Describe one form of mercury-arc rectifier, giving a diagram of connections for a service from high-tension three-phase mains to low-tension direct-current mains.

Compare its load characteristic with that of a rotary converter for similar duty. (*L.U.*)

INDEX

For List of Abbreviations, see p. xvi; List of Symbols, p. xix; List of Tables, p. xvii; General Data of Railways, Table I, p. 9–10.